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Analytical Examination of The Relationship Between Fuel Properties, Engine Efficiency, and R Factor Values

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Abstract

The variability in gasoline energy content, though most frequently not a consumer concern, is an issue of concern for vehicle manufacturers in demonstrating compliance with regulatory requirements. Advancements in both vehicle technology, test methodology, and fuel formulations have increased the level of visibility and concern with regard to the energy content of fuels used for regulatory testing.

The R factor was introduced into fuel economy calculations for vehicle certification in the late 1980s as a means of addressing batch-to-batch variations in the heating value of certification fuels and the resulting variations in fuel economy results. Although previous studies have investigated values of the R factor for modern vehicles through experimentation, subsequent engine studies have made clear that it is difficult to distinguish between the confounding factors that influence engine efficiency when R is being studied experimentally.

The present study focuses on an analytical approach to examining the heating value effects so that R values can be studied without the influence of confounding effects of other fuel properties. Data previously published for a 1.6-liter naturally-aspirated engine are used as a case study to explore the relationship between fuel properties, engine efficiency, and R factor values. The results demonstrate that engine efficiency does vary as a result of differences in heating value among fuels, although other factors that are variant among fuels also impact efficiency. R factor values depend not only on the difference in heating value between two fuels, but also on the directionality of the change and on engine operating loads. The latter is important because the reference engine efficiency point is itself a function of the engine operating condition. R factor values asymptotically approach unity as engine operating load increases. Increasing engine efficiency causes R values for a given test fuel to increase. A method is presented for which the test data from only one fuel is required to establish R factor values for individual vehicles and test cycles. An alternative method of establishing Indolene fuel economy equivalency for certification tests is also discussed.

Introduction

Over the last century fuel economy has become a ubiquitous metric for the energy efficiency of cars and trucks. Although gasoline exhibits variability in its volumetric energy content resulting from seasonal and geographic differences in formulation, this variability does not frequently rise to a level that is noticeable to consumers during real-world driving. Unfortunately, however, heating value variability is significant when considered from the point-of-view of vehicle manufacturers who must demonstrate that vehicles offered for sale comply with regulatory fuel economy standards. The formulation of gasoline used for emissions and fuel economy certification tests is considered more consistent than gasoline formulations in the marketplace. Nevertheless, it is impossible to produce gasoline without any variability in its properties over a period of many years owing to the use of different petroleum feedstocks and other unavoidable production issues that vary over time. Over the last several decades, engine efficiency and testing methodologies have improved markedly. These improvements have also caused the variations in volumetric energy content among test fuels to increase in importance.

The R factor is defined as the change in vehicle fuel economy that results from a change in the volumetric heating value of the fuel being used relative to a reference fuel. This relationship is defined in Equation 1 [1]. Both changes are expressed as a percentage change from a reference condition. The R factor was initially introduced by J.C. Ingamells, and was subsequently adopted by the Environmental Protection Agency [2,3]. It was included in certification fuel economy calculations as a corrective action to address variations in volumetric heating value of certification gasolines [1].

Equation 1. Definition of the R Factor.

$$R = \frac{\frac{VOLFE_I}{VOLFE_R} - 1}{\frac{VOLHV_I}{VOLHV_R} - 1}$$

In Equation 1, VOLHV refers to the volumetric heating value of the test (subscript I) and reference (subscript R) fuels. VOLFE refers to the volumetric fuel economy achieved with both fuels using the same subscripts as with VOLHV. In 1986 EPA established a value for R of 0.6, and as of this writing the same value is still in use for certification fuel economy calculations [1]. However, a recent change in certification fuel from an ethanol-free fuel to a fuel containing 10% ethanol has revived discussion about the appropriate value of R for modern vehicles [4]. The value of R becomes more significant as the volumetric heating value of the test fuel deviates from that of the reference fuel. Most ethanol-free fuels have heating values similar to that of the reference fuel, but the addition of ethanol results in a relatively large decrease in volumetric heating value. Experimental studies that have attempted to measure R values experimentally have obtained values that are in the range of 0.93 to 0.95 [3,5].

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Attribution of Changes in Vehicle Fuel Economy

The intent of the R factor is to enable corrections to fuel economy values that are needed to adjust to differences in the volumetric heating values of differing batches of fuel used in emissions and fuel economy certification tests. It is important to separate effects of heating value from other effects (such as those arising from differences in stoichiometric air/fuel ratio, heat-of-vaporization, etc.) on engine efficiency when establishing R values to avoid double-counting the benefits or disbenefits of these effects when calculating regulatory fuel economy values.

Figure 1 aids in illustrating attribution of fuel economy differences. The blue point and family of lines illustrate how a given volumetric fuel economy using fuel A is adjusted to an equivalent 1975 fuel economy had the original 1975 Indolene certification fuel been used for the test. The blue lines represent the results obtained when differing R values are considered. The second fuel B, with the same heating value as fuel A, causes a difference in engine efficiency and thus a different volumetric fuel economy value as the starting point instead of the blue point. For example, if fuel B resulted in a cycle-average increase in engine efficiency of 2.5%, the fuel economy for fuel B would be indicated by the red point. The red lines show how this fuel economy value would then change if adjusted to equivalency with 1975 Indolene results using different R values. Achieving a 2.5% difference in cycle-average efficiency by simply changing fuels is unlikely, but this exaggerated value makes the figure easier to comprehend. As the difference in fuel economy between fuels A and B becomes smaller, the family of lines from the red and blue points begin to overlap. Thus, using a lower value of R with a higher volumetric fuel economy can produce the same 1975 equivalent fuel economy value as using a lower value of volumetric fuel economy used with a higher value of R. Correctly calculating 1975 equivalent fuel economy values depends upon establishing R factor values that only depend on differences in heating value and are not confounded by other effects.

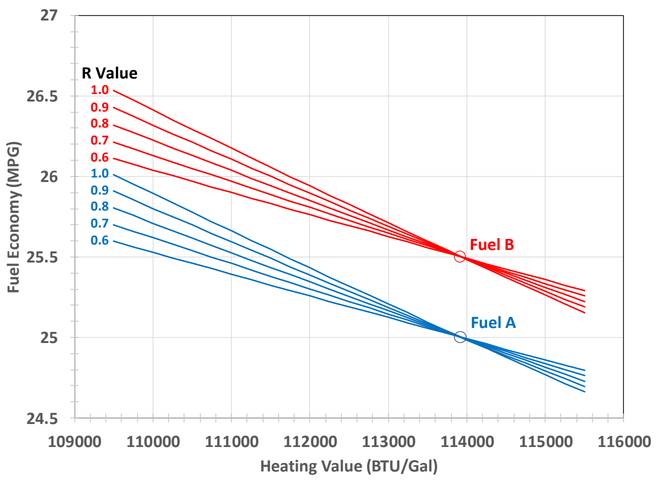

Figure 1. The application of differing R values to volumetric fuel economy values from two fuels having the same volumetric heating value yet producing different cycle fuel economies in the same vehicle shows the range of 1975 equivalent fuel economy values that can be obtained.

In practice it is difficult to achieve complete separation of changes in fuel economy that result from a difference in heating value from those that result from differences in engine efficiency that occur simultaneously. For example, a previous study identified values of R using variations in ethanol content [3]. The differences in ethanol content were not expected to produce significant differences in knock-limited operation that could influence the outcome of the study because the fuels had relatively high octane ratings; however, a subsequent study of the effects of ethanol on efficiency at part load conditions demonstrated that ethanol content does have an impact on efficiency even in conditions where knock does not occur [6]. Thus, the previous R factor study produced R factor values that may be influenced by incomplete separation of the effects of differences in engine efficiency on fuel economy from those of differences in heating value on fuel economy. Moreover, there may also be a need for correcting fuel economy results for cycles where knock-limited operation occurs. Achieving the complete separation of efficiency effects from heating-value effects necessary to correctly establish R values experimentally would likely require the construction of a statistical model that is informed by multiple tests of multiple vehicles using multiple fuels and being driven on multiple schedules. It is likely that such a test program would be expensive and would not guarantee the desired separation of effects, especially when experimental variability is included. That conundrum was the motivation for the analytical approach reported in this paper.

Engine Response to Differences in Energy Input

Mean Effective Pressure Metrics

Gross, net, friction, pumping, and brake mean effective pressures (MEP_{G}, MEP_{N}, MEP_{F}, MEP_{P}, MEP_{B}) have been used for many years as criteria for comparing work output for engines of differing displacements [7]. A similar metric, fuel mean effective pressure (MEP_{FUEL}), can be used to compare the fuel energy input for engines of differing displacements [8,9]. As with other mean effective pressure metrics, MEP_{FUEL} is expressed in units of pressure and is defined as shown in equation 2.

Equation 2. Defnition of MEP_{FUEL}.

$$MEP_{FUEL} = \frac{Fuel\ Mass\ Rate * Fuel\ Gravimetric\ Heating\ Value}{2 * Engine\ Speed * Engine\ Displacement}$$

A previous study provided a data set of example data that is presented here as a discussion of the relationship among the pressure metrics [8,9]. Data for a 1.6-liter, port-fuel-injected, naturally-aspirated engine show that the MEP_{FUEL} is converted to MEP_{G} with an an efficiency of 40%, less a combustion loss term. This relationship is shown as the green curve in Figure 2. The offset from the origin in the line is a result of the combustion loss term. Pumping work, expressed as MEP_{P}, decreases linearly as the engine output torque increases. Subtracting MEP_{P} from MEP_{G} yields MEP_{N}, shown as the orange line. The orange line has a larger slope than the green line. Friction losses for this engine are approximately constant (at fixed engine speed) with an MEP_{F} of 60 kPa. Subtracting MEP_{F} from MEP_{N} yields MEP_{B}, which characterizes the output torque of the engine. MEP_{B} is shown by the blue line. The MEP_{B} and MEP_{FUEL} ranges shown in Figure 2 are consistent with typical maximum-brake-torque (MBT) ranges where knock does not occur. The ratio of MEP_{B} to MEP_{FUEL} is equal to engine brake efficiency, η_{B}.

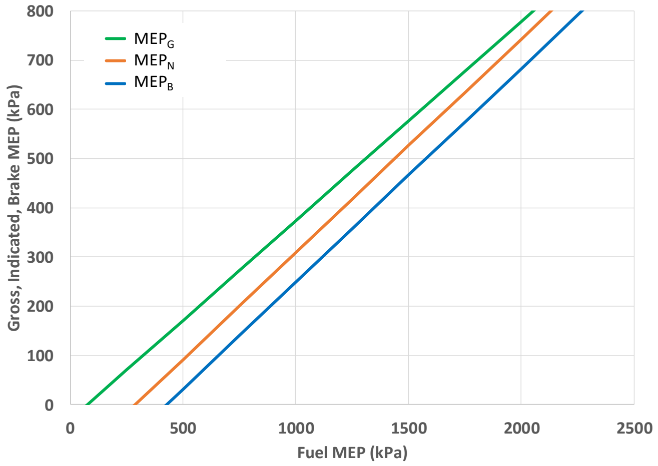

Figure 2. Mean effective pressure trends for a 1.6-liter naturally aspirated engine demonstrate the linear relationship among pressure metrics.

Hexane Isomer Example

Hexane isomers are equivalent in many ways but have differing heating values and thus provide a useful example to study relationship from Figure 2. For example, normal hexane, 2-methylpentane, and 2,2-dimethylbutane possess the same stoichiometric air/fuel ratio: 15.2. The three isomers are similar, and the variation in their heating values is minor; nevertheless, it is possible to consider different $\mathrm{MEP}_{\mathrm{FUEL}}$ values for each at a constant stoichiometric trapped charge mass. Table 1 shows their heating values and heat of vaporization.

Table 1. Heating values and heats-of-vaporization for three hexane isomers. (From Yaw's Handbook of Thermodynamic and Physical Properties of Chemical Compounds.)

Compound	Gravimetric Heating Value kJ/kg	Volumetric Heating Value kJ/l	Heat of Vaporization kJ/kg
n-hexane	44763.5	29364.9	338
2-methylpentane	44687.7	28957.6	324
2,2-dimethylbutane	44596.3	28720.0	307

In this example, 2,2-dimethylbutane isomer is understood to be the baseline fuel for operation in the MBT region, where differences in research octane number (RON) and motor octane number (MON) do not influence engine efficiency. Figure 3 shows an example using the $\mathrm{MEP}_{\mathrm{G}}$ versus $\mathrm{MEP}_{\mathrm{FUEL}}$ relationship discussed previously; the baseline fuel produces point A. If the fuel is changed at constant mass fueling rate and stoichiometry to 2-methylpentane, $\mathrm{MEP}_{\mathrm{FUEL}}$ increases because of the greater heating value of 2-methylpentane relative to 2-dimethylbutane. Since $\mathrm{MEP}_{\mathrm{FUEL}}$ increases, $\mathrm{MEP}_{\mathrm{G}}$ must also increase. This condition is denoted by point B. Similarly, shifting to n-hexane results in point C. The same $\mathrm{MEP}_{\mathrm{G}}$ as for points B and C could also be obtained if the engine was throttled to a lesser degree while using the baseline fuel. For clarity, these points will be called D and E. In other words, operation with an isomer that has a greater heating value is analogous to operation with the baseline fuel at a higher trapped charge mass, all other things being equal.

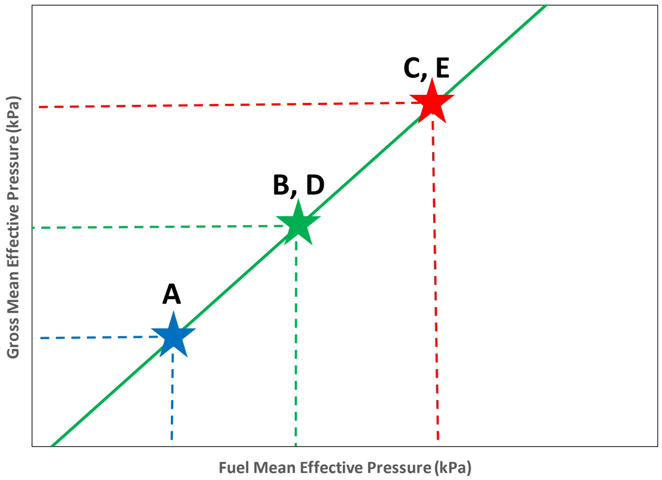

Figure 3. Operation with the three hexane isomers results in production of gross mean effective pressure according to the fixed fuel conversion efficiency in the MBT region.

Figure 4 shows the $\mathrm{MEP}_{\mathrm{P}}$ versus $\mathrm{MEP}_{\mathrm{FUEL}}$ relationship for the 1.6-liter engine. Operation with the baseline fuel (2,2-dimethylbutane) results in point A. Since the three isomers have the same stoichiometric air/fuel ratio, increasing $\mathrm{MEP}_{\mathrm{FUEL}}$ can occur without changing the charge mass trapped in the cylinders. In this case, points B and C result as previously discussed. Points B and C have the same $\mathrm{MEP}_{\mathrm{P}}$ as point A. If points A, D, and E are obtained by use of only the baseline isomer, the fuel/air charge mass must be adjusted to achieve the needed variation in $\mathrm{MEP}_{\mathrm{FUEL}}$. Changing the charge mass by adjusting the throttle results in points A, D, and E having different $\mathrm{MEP}_{\mathrm{P}}$ requirements. The difference in $\mathrm{MEP}_{\mathrm{P}}$ at the same $\mathrm{MEP}_{\mathrm{FUEL}}$ for these conditions are indicated in Figure 4 as $\Delta\mathrm{MEP}_{\mathrm{P,B}}$ and $\Delta\mathrm{MEP}_{\mathrm{P,C}}$.

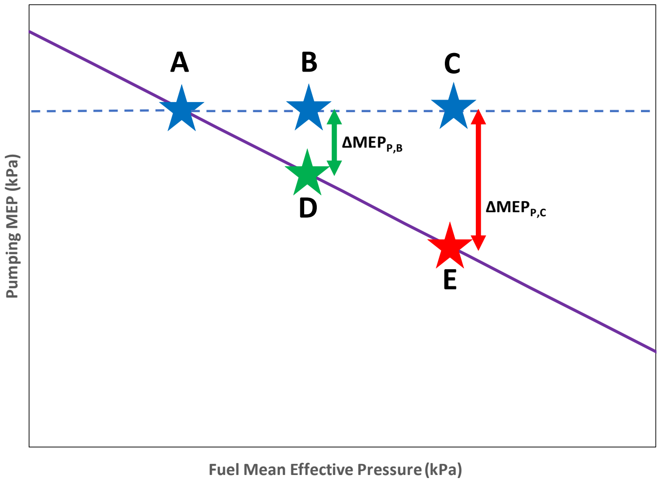

Figure 4. Use of isomers with increasing heating value relative to a use of a single isomer with increasing charge mass causes differences in $\mathrm{MEP}_{\mathrm{P}}$ to emerge as $\mathrm{MEP}_{\mathrm{FUEL}}$ increases.

The differences in $\mathrm{MEP}_{\mathrm{P}}$ from point B to point D and point C to point E cause points B and C to exhibit smaller values of $\mathrm{MEP}_{\mathrm{N}}$ than points D and E. Since $\mathrm{MEP}_{\mathrm{F}}$ is constant, $\mathrm{MEP}_{\mathrm{B}}$ is also lower for points B and C than for points D and E, resulting in lower values of brake efficiency for points B and C than points D and E. Thus, use of the isomers with increased heating value relative to the baseline isomer causes brake efficiency to decrease when considered at equal $\mathrm{MEP}_{\mathrm{B}}$.

The discussion thus far has focused on engine operation where knock does not occur. The linear nature of the MEP_{FUEL} relationship to MEP_{BRAKE} breaks down as combustion phasing is retarded or air/fuel ratio is enriched to avoid the occurrence of knock. Provided that the two fuels being studied have the same anti-knock performance, deviation from a linear relationship between MEP_{FUEL} and MEP_{BRAKE} will also be the same for both fuels at a given value of MEP_{BRAKE}. If differences in the anti-knock properties of the two fuels do exist, these differences will cause the volumetric fuel economy results for the two fuels to diverge but should not impact the R factor value for one fuel versus the other.

It is important to acknowledge that a decrease in efficiency resulting from increased fuel heating value is a theoretical construct; other effects introduced by changing fuel chemistry may have a similar or higher impact on efficiency. The effects can include differences in stoichiometric air/fuel ratio, heat-of-vaporization (HoV), and laminar flame speed, for example. The current discussion focuses on separating these impacts from that of heating value to correctly assess values of R. The relative importance of other related effects is discussed in a later section of the paper.

Quantifying Effect of Heating Value Difference on η_B

As shown in Figure 2, the imposition of pumping work, MEP_P, reduces MEP_G to MEP_N. Because MEP_F is constant, the slope of the MEP_N versus MEP_{FUEL} line is equal to the slope of the MEP_B versus MEP_{FUEL} line. The decreased MEP_P noted for points D and E relative to points B and C is the reason that the slope of the MEP_B versus MEP_{FUEL} line is greater than the slope of the MEP_G versus MEP_{FUEL} line. Thus, it is possible to assess the difference in MEP_P for those points by knowing only the slope and intercept of the MEP_B versus MEP_{FUEL} line. For the 1.6-liter engine, the slope of the MEP_B versus MEP_{FUEL} line is 0.434 and the intercept is -185 kPa. Figure 5 shows η_B versus MEP_{FUEL} for this example. The percentage change in efficiency for a given change in MEP_{FUEL} is nonlinear, with greater impact at lighter loads. For example, at a MEP_{FUEL} of 1,000 kPa the efficiency increase posed by a 1% increase in MEP_{FUEL} is 0.2 points of efficiency. At a MEP_{FUEL} of 2,000 kPa a 1% increase in MEP_{FUEL} results in a gain of 0.1 efficiency point. Thus, at these two conditions, increasing the gravimetric heating value of the fuel by 1% will reduce the engine efficiency by 0.2 and 0.1 efficiency points, respectively, to retain a fixed MEP_B.

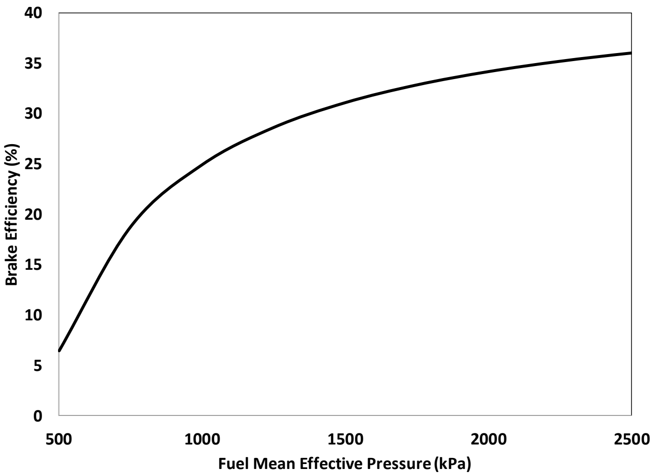

Figure 5. Brake engine efficiency, η_B, increases nonlinearly as fuel mean effective pressure increases.

R Factor Dependence on Engine Efficiency

The previous section of the paper discussed the impact of providing marginally higher or lower MEP_{FUEL} to the engine on η_B. This section focuses on describing how changes in η_B cause changes in R factor. A previous paper derived a relationship between R, the volumetric heating values of the test and reference fuels, and the cycle average engine efficiency when the test and reference fuels were used [3]. This derivation was based on a given vehicle operating on a given test cycle. Since the loads placed on the powertrain are the same regardless of which fuel is used, any difference in fuel economy must result from a combination of changes in engine efficiency and fuel heating value. Equation 3 shows how R depends upon the cycle-average engine efficiency. VOLHV represents the volumetric; heating value, η represents the brake engine efficiency, subscript *I* represents the test fuel, and subscript *R* represents the reference fuel.

Equation 3. Relationship between R, heating value, and engine efficiency.

$$R = \frac{VOLHV_I * \eta_I - VOLHV_R * \eta_R}{(VOLHV_I - VOLHV_R) * \eta_R}$$

The dependence of R on the cycle-average efficiencies with the test and reference fuel highlights the fact that the engine experiences a range of MEP_B conditions in any given driving cycle. For clarity, R^* will be used to reflect an evaluation of the impact of fuel properties at a particular engine output condition. R is equal to the cycle-average R^* for a given drive cycle.

If 2,2-dimethybutane is used as a baseline fuel, 2-methylpentane exhibits a gravimetric heating value that is 0.20% higher but a volumetric heating value that is 0.83% higher. These increases for n-hexane relative to 2,2-dimethylbutane are 0.37% and 2.25% higher, respectively. Figure 6 shows the R^* factor curves that reflect the differences in efficiency and heating value among the hexane isomers for the 1.6-liter engine. The curves demonstrate that R^* is a function of both the difference in heating value and the baseline MEP_{FUEL} used for the evaluation. It is also useful to consider the relationship between R^* and MEP_B instead of MEP_{FUEL}. Figure 7 shows that relationship. The red curve for 2-methylpentane shows that R^* meets or exceeds 0.9 if MEP_B is greater than 467 kPa. For n-hexane, R^* meets or exceeds 0.9 if MEP_B is greater than 315 kPa. R^* meets or exceeds a value of 0.9 at a MEP_B of 100 kPa if the volumetric heating value increases by least 7.4%. Such an increase would guarantee that R^* is greater than 0.9 for essentially the entire engine operating map except for the idle condition. Carrying out the calculation of R^* to extreme values of MEP_{FUEL} demonstrates that R^* asymptotically approaches unity as MEP_{FUEL} approaches infinity. This behavior is a result of decreased mathematical difference between MEP_G and MEP_N as MEP_{FUEL} increases.

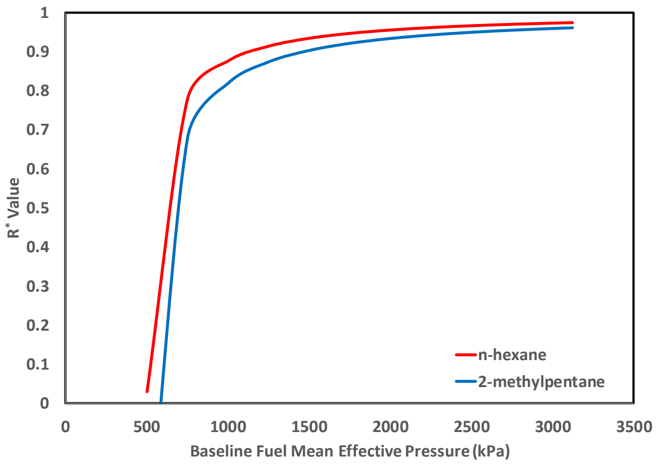

Figure 6. R^* versus baseline fuel mean effective pressure for n-hexane and 2-methylpentane with 2,2-dimethylbutane as the reference case show the impact of fuel heating value changes on R^*.

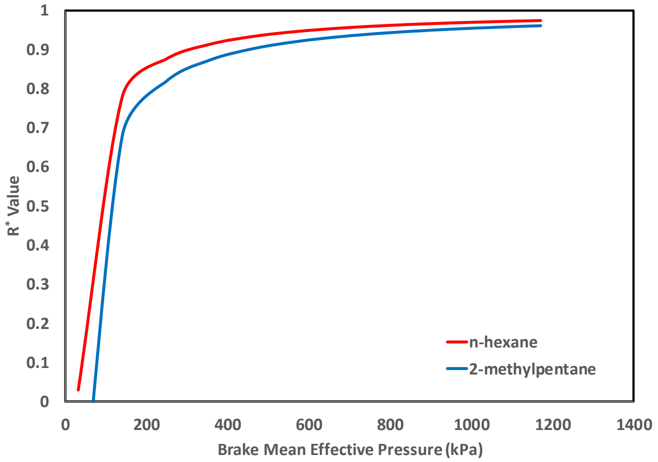

Figure 7. R^* versus brake mean effective pressure for n-hexane and 2-methylpentane with 2,2-dimethylbutane as the reference case show that for this fuel change, R^* is greater than 0.9 at a MEPB of 467 kPa.

Considering the three hexane isomers while using n-hexane as the baseline fuel instead of 2,2-dimethybutane allows investigation of decreases in heating value in the same way that increases have just been examined. These results are shown in Figure 8. Two curves are shown, but for this directional change the magnitude of impact of the percentage change in heating value is decreased. This decrease results in the two curves nearly overlapping one another. For decreasing heating values, the calculated value of R^* at a fixed MEP_{FUEL} is lower than for increasing heating values. This result is logical because the gain in η_B for decreasing gravimetric heating value at a given MEP_{FUEL} is larger than the loss in η_B for the same magnitude decrease in gravimetric heating value at the same baseline MEP_{FUEL}. As was observed for heating value increases, the value of R^* for decreasing heating value is less than unity but asymptotically approaches unity as baseline MEP_{FUEL} increases.

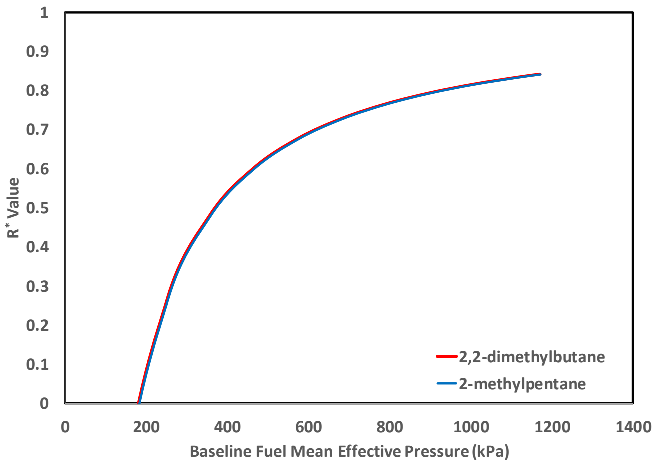

Figure 8. Examination of R^* with n-hexane as the baseline fuel. The resulting R^* trends are essentially the same for 2-methylpentane and 2,2-dimethylbutane.

To summarize the effects outlined in this section of the paper, the heating value of a fuel indeed impacts brake engine efficiency and can be examined separately from other fuel properties that are co-variant with heating value. Major findings include the following:

- Increasing fuel gravimetric heating value decreases engine brake efficiency when compared on a fixed MEP_{FUEL} or MEP_B basis. The opposite effect occurs when gravimetric heating value is reduced. This effect occurs because of the need to adjust trapped charge mass and the resulting difference in MEP_P to achieve a fixed value of MEP_B for fuels with differing heating values while maintaining a stoichiometric air/fuel ratio.
- Calculated R^* values depend on the efficiency change that results from a heating value difference. As engine efficiency varies with MEP_{FUEL}, so must R^*.
- Directionality of the heating value change is important; R^* has different values depending on whether fuel heating value increases or decreases, even at the same baseline MEP_{FUEL}.

Confounding Effects from Other Fuel Properties

Three of the confounding effects from fuel properties that are co-variant with volumetric heating values may be quite large, three cases are discussed in this paper. Changes in stoichiometric air/fuel ratio, changes in HoV, and changes (such as flame speed) that may cause fuel combustion efficiency to vary. Ethanol blending results in a significant change in the volumetric heating value of gasoline and is a useful means to explore the impacts of stoichiometric air/fuel ratio, HoV, and fuel conversion efficiency. Table 2 shows the heating values and HoVs of the three hexane isomers as blends containing 10% ethanol.

Table 2. Blending the hexane isomers with ethanol reduces their heating values and increases their heats-of-vaporization.

Compound	Gravimetric Heating Value kJ/kg	Volumetric Heating Value* kJ/l	Heat of Vaporization kJ/kg
10% ethanol / n-hexane	42967.15	28762.2	390
10% ethanol / 2-methylpentane	42898.93	28407.7	377
10% ethanol / 2,2-dimethylbutane	42816.67	28199.1	362

* Blend density assumed to be volume-weighted combination of the densities of the pure compounds.

Differences in Stoichiometric Air/Fuel Ratio

Blending any of the three example isomers of hexane with 10% ethanol reduces the stoichiometric air/fuel ratio of the fuel to 14.6. At fixed MEP_P, that difference results in a stoichiometric mixture with 3.3% higher MEP_{FUEL}. The difference results in a 0.37-point decline in η_B at a baseline MEP_{FUEL} of 2,000 kPa for the ethanol blend compared with n-hexane. The heating value change from blending 10% ethanol with n-hexane produces a fuel that has 4% lower gravimetric heating value. That effect simultaneously produces a 0.39-point increase in η_B at the baseline 2,000 kPa MEP_{FUEL} condition, causing the two effects to nearly cancel.

Differences in Heat-of-Vaporization

HoV of the fuel influences MEP_P in different ways, depending upon engine design. The maximum effect occurs if the fuel absorbs the HoV entirely from the incoming fresh air, resulting in a cooler, denser charge. The denser charge results in an increased MEP_{FUEL} at constant MEP_P. For n-hexane, blending with 10% ethanol increases HoV on a gravimetric basis by 15%. However, the difference in charge cooling is 20% greater on a stoichiometric-charge basis for the mixture because a stoichiometric mixture of 10% ethanol with n-hexane has a lower stoichiometric air/fuel ratio than hexane alone. Assuming that the increased HoV is drawn from the fresh air charge, the stoichiometric charge for the mixture is 1.9% denser than that of the hexane alone. If MEP_P is held constant, 1.9% more fresh charge mass is trapped in the cylinder, resulting in 1.9% higher MEP_{FUEL}. If MEP_P is then increased for the higher-HoV fuel to provide fixed MEP_B for the two fuels, η_B for the fuel with higher HoV declines. In this case, the decline is 0.76 points, which may occur simultaneously with the other effects discussed previously.

Differences that Affect Fuel Conversion Efficiency

Differences in fuel blends can create complex interactions that impact fuel conversion efficiency. For example, studies have shown that lower in-cylinder temperatures realized when ethanol is blended into gasoline result in efficiency gains in combustion and that ethanol blending changes the molar expansion ratio [6,10]. Such effects can occur simultaneously with the other confounding effects that have already been discussed. If the changes act to increase fuel conversion efficiency, they effectively increase MEP_G at a fixed MEP_P, leading to a decrease in η_B compared with a baseline fuel with lower fuel conversion efficiency if the comparison occurs at fixed MEP_B.

R^* for Differences in Certification Fuels

The preceding sections have demonstrated that R^* is a function of both the efficiency profile of the engine and the heating value of the fuels in question. The directionality and relative magnitude of confounding effects have also been explored. Evaluating how R^* varies for the change in certification fuels from EPA's ethanol-free Tier 2 fuel to the E10 Tier 3 fuel is of interest. Batches of each a Tier 2 and Tier 3 certification gasoline have the heating values and stoichiometric air/fuel ratios listed in Table 3. Values for Indolene, (the reference fuel for the Corporate Average Fuel Economy calculation) are also shown. As noted previously, ethanol blending lowers the stoichiometric air/fuel ratio of a fuel blend when compared to an ethanol-free blend. Just as in the hexane isomer example, the effects of heating value and stoichiometric air/fuel ratio on η_B partially offset one another for the change from Indolene to the Tier 3 certification fuel.

Table 3. Heating values for three certification gasoline fuels.

Fuel	**Gravimetric Heating Value (kJ/kg)**	**Volumetric Heating Value (kJ/l)**	**Stoichiometric Air/Fuel Ratio**
Tier 2 (E0, 97 RON)	42813	31724	14.5
Tier 3 (E10, 92.3 RON)	41430	30936	14.0
Indolene*	42980	31716	14.5

*Indolene property values from SAE Paper 930138.

Figure 9 shows the calculated R^* values for the Tier 3 fuel with Indolene as the base fuel for the 1.6-liter engine example. Directionally, R^* values for the Tier 3 fuel agree with those observed for the hexane isomers when heating values decreased. R^* values greater than 3 were obtained for the Tier 2 fuel over the same calculation range. This outcome is a result of the fact that the Tier 2 fuel has a lower gravimetric heating value but a higher volumetric heating value than Indolene. Directionally, these cause an increase in volumetric heating value at the same time as an increase in engine efficiency. Thus, the volumetric fuel economy increases more than would be suggested by the volumetric fuel economy change alone, creating an R^* greater than unity. R^* values greater than unity can also occur when there is a decrease in volumetric heating value at the same time as engine efficiency decreases. This situation could occur if the test fuel gravimetric heating value was higher and the volumetric heating value was lower than the reference fuel value.

As discussed previously, the value of R becomes significant in terms of calculated fuel economy as the test fuel heating value diverges from that of the reference fuel. R and R^* values much greater than unity result from a small difference in heating values in the denominator of equations 1 and 3. The result of both equations approaches infinity as the difference in heating values approaches zero. Thus, values of R and R^* significantly greater than unity do not lead to large changes in calculated Indolene-equivalent fuel economy.

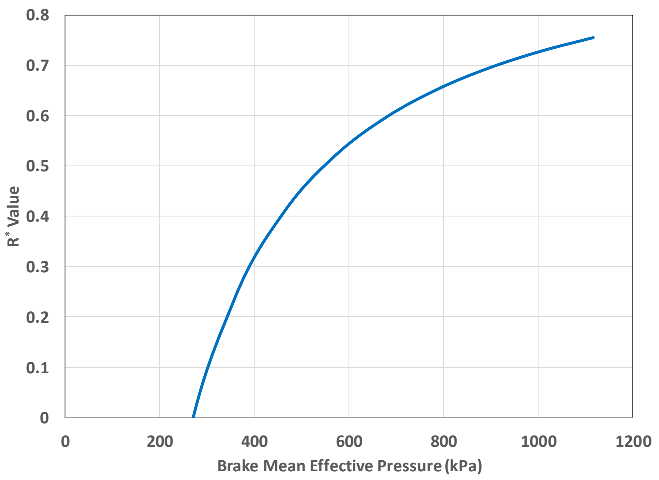

Figure 9. R^* values for a Tier 3 certification fuel with Indolene as the baseline fuel at varying brake mean effective pressure levels are lower than those calculated for a decrease in heating value with hexane isomers.

Sensitivity of R^* to Engine Efficiency Differences

Thus far, calculations of R^* in this paper have focused on the efficiency curve for a single engine. Because efficiency also varies among engines, it is appropriate to examine how sensitive R^* calculations are to changes in engine efficiency. Published data enable performing a regression between MEP_B and MEP_{FUEL} to obtain the equations of regression lines for use in this analysis [9,11,12]. Regression results for several engines are shown in Table 4. The engines in the table include a breadth of technologies, from model year 1985 to present.

Table 4. MEP_B versus MEP_{FUEL} regression results for several engines from 1985 to the present.

Engine	Displacement (liters)	Compression Ratio	Fueling / Induction	Regression Line*	
				Slope	Intercept (kPa)
Ford I-4	1.6	11	PFI / NA	0.434	185
Ford I-4	2	10	PFI / NA	0.42	158
Ford I-4	2	12	DI / NA	0.447	175
Ford V-6	2.7	9	PFI / TC	0.401	196
Ford I-3	1	10	DI / TC	0.43	195
Ford V-6	2.7	10	DI / TC	0.408	135
Pontiac I-4	1.8	9	PFI / NA	0.407	181
GM I-4	2.26	9.5	PFI / NA	0.395	140
Nissan V-6	3	9	TBI / NA	0.41	194
Late 1990s Average	2.4 - 6.8	8.6 - 9.6	PFI / NA	0.405	172
Toyota I-4 Atkinson	2.5	13	DI + PFI / NA	0.487	166

PFI = Port Fuel Injection, TBI = Throttle Body Injection, DI = Direct Injection

NA = Naturally Aspirated, TC = Turbocharged

$* MEP_B = Slope * MEP_{FUEL} - Intercept$

In general, engines tend to have an MEP_B/MEP_{FUEL} relationship characterized by a slope that is close to 0.4, but with an upwards trend in the slope with increasing compression ratio. That trend is consistent with the use of increased compression ratio to enhance engine efficiency [7,13,14]. Future engines are likely to gain efficiency relative to the 1.6-liter engine discussed in this paper. The Toyota 2.5-liter engine has a slope and an intercept that are approximately 10% improvements on the values for the 1.6-liter engine and thus is a useful benchmark for the present discussion. Figure 10 shows R^* curves for three cases: improvement in slope, improvement in intercept, and improvement in both slope and intercept. The improved slope and intercept values are from the Toyota 2.5-liter engine. As in Figure 9, these R^* values describe the change from Indolene to Tier 3 certification gasoline.

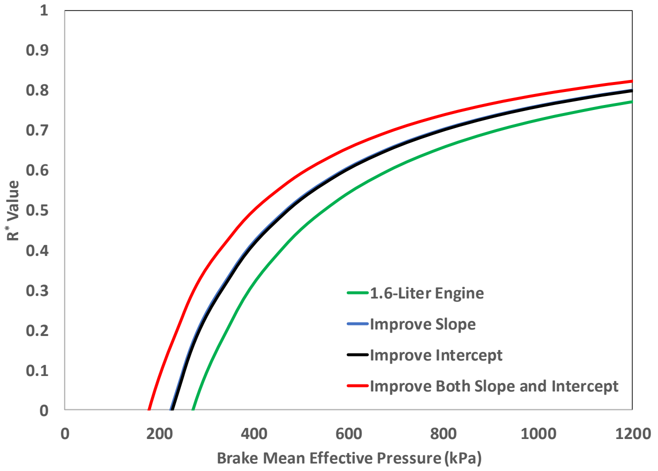

Figure 10. Comparison of R curves resulting from improvements in engine efficiency shows that increased engine efficiency results in higher R^* values.*

Improving slope or intercept to provide higher engine efficiency moves the calculated R^* values at all MEP_B levels to higher values. R^* values resulting from either approach are very similar. Improving both slope and intercept further increases R^* values. The results demonstrate that R^* values for the same fuel change to shift upwards as engine efficiency improves.

Vehicle-Specific R Factor Values

To date, R factor values have been established by observing the changes in volumetric fuel economy of multiple fuels with differing heating values. As demonstrated herein, these observations cannot avoid confounding the true differences due solely to differences in volumetric heating value with related fuel property effects on engine efficiency. This section presents a method that can be used to correctly establish R factor values for individual vehicles and drive cycles. The discussions in this section presume that the reference fuel is 1975 Indolene, as used in fuel economy certification calculations in the United States.

Step 1: Establish $MEP_{B,W}$ versus MEP_{FUEL}

In the examples already discussed, the relationship between MEP_B and MEP_{FUEL} was used to establish a theoretical framework that allowed calculation of the impact of changes in gravimetric heating value on engine efficiency. A means of establishing that relationship in a vehicle without knowledge of the engine output torque is needed. Defining $MEP_{B,W}$ in the same way as MEP_B, but using the measured wheel torque, can provide the information needed. The first step in the process, measuring $MEP_{B,W}$ as a function of MEP_{FUEL}, can be accomplished by operating the vehicle at fixed speed (or series of speeds) and varying wheel torque on a chassis dynamometer by either adjusting the simulated road grade or parametrically varying the road load coefficients. The torque variation should be large enough to cover the MBT range of the engine. Knock onset for many engines occurs at a MEP_B of about 800 kPa. Because the driveline imposes an additional loss term, 800 kPa MEP_B corresponds to a lower $MEP_{B,W}$. Assuming that the driveline efficiency is at least 63%, the corresponding $MEP_{B,W}$ will be no less than 500 kPa. A regression of the $MEP_{B,W}$ versus fuel consumption measurements expressed as MEP_{FUEL} will produce a regression line that provides the needed efficiency versus MEP_{FUEL} relationship for the vehicle. Since gear changes cause MEP_B and $MEP_{B,W}$ to change according to the gear ratio selected, $MEP_{B,W}$ must be adjusted accordingly so that it is linearly related to MEP_B regardless of the gear selected.

This step assumes that wheel brake torque is linearly related to engine brake torque, as would be the case with conventional, non-hybrid vehicles in a fixed gear. The range of operating strategies for hybrid vehicles suggests that defining R factor values for them merits its own study. In the absence of such a study, a directional assessment may suffice. In most cases, hybridization strategies tend to reduce low-MEP_B operation of the engine because doing so is an effective means of improving efficiency. At moderate MEP_B values, the asymptotic behavior of R with MEP_B may allow selection of a fixed R factor value for simplicity.

Step 2: Establish $MEP_{B,W}$ Points During Drive Cycles

The next piece of information needed is the weighted average MEP_B. Average MEP_B calculated by weighting second-by-second MEPB with the corresponding fuel consumption would ideally be used but is likely inconvenient to obtain during certification tests. Use of a time-weighted average MEP_B is not likely to introduce a significant error and would be easier to obtain for a breadth of drive cycles.

Step 3: Calculate η_I and η_R

The relationship established in step 1 is used to calculate the efficiency values when using the test and reference fuels. Because the relationship established in step 1 was determined with a modern test fuel, the linear relationship defines the MEP_B and MEP_{FUEL} that together allow calculation of η_I. When the weighted average MEP_B is known for the cycle of interest, the MEP_B versus MEP_{FUEL} linear regression can be used to calculate $MEP_{FUEL,I}$. $MEP_{FUEL,I}$ and the weighted average MEP_B for the cycle, are used to calculate η_I.

When the percentage change in the gravimetric heating value of the test fuel relative to the reference fuel is calculated, a positive percentage change indicates that the test fuel has a higher gravimetric heating value than the reference fuel. The percentage change is applied to the $MEP_{FUEL,I}$ value calculated for the test fuel to find $MEP_{FUEL,R}$. If the reference fuel has a lower gravimetric heating value than the test fuel, $MEP_{FUEL,R}$ will be lower than $MEP_{FUEL,I}$. The linear relationship determined in step 1 is used to calculate $MEP_{B,R}$ based on $MEP_{FUEL,R}$. The value for η_X is calculated by dividing $MEP_{B,R}$ by $MEP_{FUEL,R}$. The value for $\Delta\eta$ is obtained by subtracting η_X from η_I. Finally, calculate η_R by subtracting $\Delta\eta$ from η_I. If the reference fuel has a lower gravimetric heating value than the test fuel, η_R will be higher than η_I.

Step 4: Calculate R for the Vehicle and Drive Cycle

Equation 3 is used with the efficiency values η_R and η_I calculated in step 3 with the known volumetric heating values of the two fuels to calculate R for the cycle of interest. Since the two efficiencies were calculated based on weighted-average MEP_B values for the cycle, the calculation produces R instead of R^*. This calculation inherently assumes that transient effects (e.g. air/fuel ratio control, cylinder-to-cylinder imbalances) average out when differences between fuels for a given drive cycle are being considered. If systematic differences in the factors between fuels exist, it is not appropriate to include them in calculating R values. Instead, the effects will manifest themselves as changes in the volumetric fuel economy measurements to which R will be applied to calculate an Indolene-equivalent fuel economy.

Using Carbon Emissions to Establish Fuel Economy Equivalency Instead of Heating Values

The complexities of establishing values of R for individual vehicles and cycles as well as the breadth of possible designs for hybrid vehicle powertrains present a challenge for continuing to make use of the R factor for future fuel economy calculations. Additionally, correctly establishing heating values for fuels containing ethanol can be problematic [15]. Using carbon emissions during a certification test may represent a more straightforward method to establish fuel economy equivalency than is offered by comparisons of volumetric heating value.

Carbon weight fraction of certification fuels is already an established and routine measurement. Carbon emissions during certification tests are measured by summing the contributions from CO_2, CO, and unburned hydrocarbons to obtain a metric for mass of carbon per mile. The measurements allow the calculation of fuel volume consumed. That calculation is the basis of the calculation of fuel economy for certification tests if the terms related to R and the heating values are not considered. Calculation of the Indolene-equivalent fuel economy can be accomplished by dividing the mass of carbon per gallon for Indolene by the carbon mass emissions per mile.

This procedural change likely introduces a discontinuity in the resulting fuel economy values relative to the present method, especially given the likely shift to ethanol-blended certification fuels for fuel economy tests. The Tier 2 certification fuel listed above produces 0.3% more carbon emissions than Indolene for the same energy use, but the Tier 3 fuel produces 0.8% less carbon emissions compared to Indolene for the same energy use. Hence, a vehicle with a fixed energy use on a given cycle would be reported to have differing Indolene-equivalent fuel economy values depending on whether a Tier 2 or a Tier 3 fuel was used for the test. This discontinuity could be accepted as insignificant or an offset parameter could be introduced to eliminate this issue. Such an offset could be applied either to statutory fuel economy requirements or to the Indolene carbon equivalency calculation.

Adjusting the statutory fuel economy requirements so that the carbon balance-based fuel economy result from a given test is used in certification with no adjustment for its heating value is the most straightforward in terms of technical accuracy and testing simplicity. The chemical makeup of Tier 3 certification fuel is specified to a greater degree than past certification fuels [4]. The greater degree of constraint on the chemical makeup of the fuel likely reduces the impact of batch-to-batch differences on vehicle emissions and fuel economy performance. However, the need to adjust the statutory fuel economy requirements is a necessary and non-trivial process that may be perceived as a drawback to this approach. Currently, fuel economy standards beyond model year 2021 are under review, potentially providing an opportunity to adjust the standards so that the fuel economy obtained when Tier 3 fuel is used could be adopted for CAFE compliance [16].

Conclusions

- An analytical study demonstrates that engine efficiency changes when fuels with differing heating values are used. This effect is purely a result of the difference in heating values.
- Confounding factors that accompany a change in fuel heating value make it very difficult to correctly assess R factor values through experimentation.

- The impact of confounding factors associated with a fuel change may be of the same order-of-magnitude in terms of their impact on engine efficiency as changes in heating value. These impacts may be directionally additive to or subtractive from differences in efficiency that result from changes in heating value.
- R^* values depend on the engine operating condition as well as the magnitude and direction of the change in heating value. R^* values asymptotically approach unity at high values of MEP_{FUEL} or MEP_B.
- R^* values for a Tier 3 E10 test fuel using Indolene as a reference fuel calculated in the present study are lower than those measured in recent experimental studies with ethanol-blended fuels.
- Improving engine efficiency for the same test and reference fuel results in higher values of R^* at all MEP_B levels.
- A method is presented that can enable characterization of the R factor for individual vehicles and using laboratory tests of a single fuel, with knowledge of the fuel properties of at least two fuels.
- Alternative means for establishing fuel economy (such as the use of a carbon equivalency or adoption of fuel economy results when a tier 3 fuel is used) may be more convenient solutions than continued use of the R factor in certification tests.

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Definitions/Abbreviations

EPA	Environmental Protection Agency
HoV	Heat-of-vaporization

MBT	Maximum brake torque
MEPB	Brake mean effective pressure
MEPF	Friction mean effective pressure
MEPFUEL	Fuel mean effective pressure
MEPG	Gross mean effective pressure
MEPN	Net mean effective pressure
MEPP	Pumping mean effective pressure
MON	Motor octane number
ηB	Brake engine efficiency
ηI	Brake engine efficiency using a test fuel
ηR	Brake engine efficiency using a reference fuel
RON	Research octane number
R	R factor (for a drive cycle)
R*	R evaluated at a particular engine condition, not for a drive cycle.
VOLFEI	Volumetric fuel economy for a test fuel.
VOLFER	Volumetric fuel economy for a reference fuel (typically Indolene).
VOLHVI	Volumetric heating value for a test fuel.
VOLHVR	Volumetric heating value for a reference fuel (typically Indolene).