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Technical Support Report for Regulatory Action

Methodology for Calculation of Diesel Fuel to Gasoline Fuel Economy Equivalence Factors

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Summary

This study presents a methodology for calculating energy equivalence conversion factors for fuel economy of diesel fueled passenger vehicles relative to gasoline-fueled passenger vehicles. Both differences in volumetric heating values for diesel and gasoline fuels as well as process energy savings attributable to refinery production shifts to diesel fuels are treated in the methodology.

Three illustrative cases were computed utilizing the developed methodology; a case representing the maximum process energy savings, a case where the ratio of diesel to gasoline fuel production (for automotive usage) becomes 20%/80%, and a case where diesel fuel consumption increases by only 1% relative to gasoline consumption.

The three cases produce numerical differences of varying significance. However, since diesel fuel consumption by automobiles is miniscule at present and projections of diesel passenger car sales would have to be speculative at best it is recommended that for the near-term only differences in volumetric heating values for the two fuels be considered for computing the conversion factor.

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Approved - Division Director

Statement of Problem

The objective of this study is to compute a fuel economy conversion factor for the diesel-fueled vehicle to place it on an energy equivalent basis with the gasoline-fueled vehicle. By energy equivalence it is meant that adjustments to the fuel economy of the diesel fueled vehicle should be made to account for net differences in heat content per unit volume between gasoline and diesel fuels and process energy savings (or penalties) resultant from refinery production shifts to diesel fuel. In effect this approach results in a conversion factor that indirectly adjusts fuel economy on a crude oil input basis although the computations are normalized to a gasoline volume unit, (i.e., miles per gallon gasoline equivalent) and the savings are allocated completely to diesel fuel.

Sources of Data

The conversion of diesel vehicle fuel economy to a gasoline equivalent basis to account for the differences in the net heat content of diesel and gasoline fuels is relatively straight-forward and requires knowledge only of specific gravity and heat of combustion for the fuels. These values were obtained from SAE paper 740522 and SAE Standard J1082.

The adjustment for differences in process energy consumption is not straight-forward as there exists a wide divergence of opinion in industry as to the magnitude of this difference; however, there is general agreement that diesel fuel production would result in savings of energy at the refinery at least up to the point where diesel fuel becomes 50% of the automotive fuel production.

As part of its diesel vehicle evaluation program EPA contracted with the Exxon Research and Engineering Company (Contract No. 68-01-2112) to "study the effects of changing the proportions of automotive distillate and gasoline produced by petroleum refining". This study was completed in July 1974 and was selected as the principal source of data for this study.

The main conclusions of the Exxon Study were:

(1) Maximum process energy savings were obtained when the amount of automotive distillate (diesel fuel) produced was approximately half the total automotive fuel output (on a BTU basis).*

(2) Beyond a 55/45 ratio of automotive distillate/gasoline, process energy consumption, automotive fuel cost, and investment all increased.

(3) At about a 70/30 ratio, energy consumption and costs approximated the base case values (the base case assumed a 10/90 ratio).

*Exxon used the term "automotive" to include trucks, cars, buses. This definition will also be utilized in this report. Exxon also used the term "distillate" to mean diesel fuel. Likewise, this definition will be used in this report.

(4) Beyond the 70/30 automotive distillate/gasoline ratio, energy consumption and costs increased sharply. That is, a penalty in energy consumption and cost was predicted for further increase in distillate usage.

(5) The energy consumption was influenced by heavy fuel oil production with slightly higher consumption of energy at the refinery for the case of low volumes of heavy oil production (this is the current case as most heavy oils are imported---the modern US refinery maximizes refined product yields for economic reasons). However, for purpose of this study the relatively small differences in energy consumption caused by differences in heavy oil production is ignored and the maximum savings in each case is used.

(6) The maximum savings in energy consumption (55/45 ratio of distillate to gasoline) were about 2% relative to the base case. This savings is equivalent to a 2% savings in crude oil. When related to the total production of automotive fuel the percentage would be almost doubled (because the total automotive fuel output was 60% to 51% of the total refinery product output with the difference attributed to the range in heavy oil production depending upon whether it is imported or produced domestically). It is reasonable to attribute the energy savings entirely to automotive fuel since the yields of all other products are likely to remain constant.* (This assumption may be subject to argument since the fuel economy standards will force reduced consumption of gasoline and a change in the ratio of gasoline to diesel fuel production of itself.)

(7) The actual process energy savings versus proportion of distillate to total automotive fuel production is shown plotted in figure (1).

Computational Results

The normalization of diesel vehicle fuel economy to the gasoline fueled vehicle fuel economy to adjust for the differences in the heating values of the fuels is straight-forward and is described in appendix I. On a btu-content basis the conversion factors are:

Diesel fuel # 1

Mpg (Indolene HO III equivalent) = 0.905 x Mpg Diesel

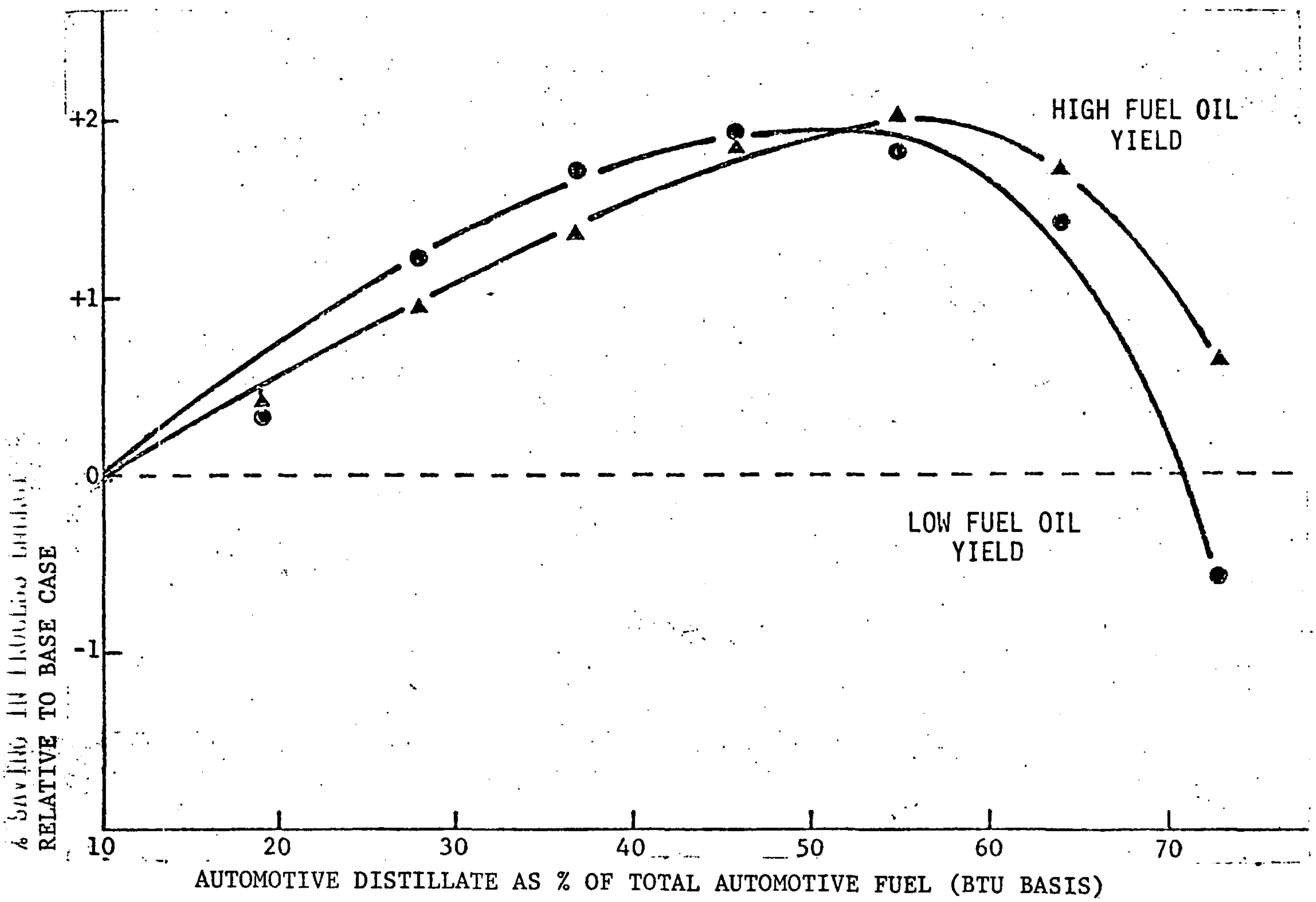
Diesel fuel # 2

Mpg (Indolene HO III equivalent) = 0.873 x Mpg Diesel

*This was the conclusion of Exxon. In this study an arguement will be made to attribute all savings to the diesel fuel account. However, other philosophies of allocation of savings are possible and will be discussed also.

FIGURE 1

	Automotive Distillate as % of Total Automotive Fuel*							
	10	19	28	37	46	55	64	73
% SAVINGS RELATIVE TO BASE CASE								
Low fuel oil yield	Base	0.3	1.2	1.7	1.9	1.8	1.4	-0.6
High fuel oil yield	Base	0.4	0.9	1.3	1.8	2.0	1.7	0.6



The conversion factors above consider only equivalence of the two primary fuels on a product-out basis.* Since process energy consumption at the refinery is influenced by the product yield (that is, the mix of products refined), adjustments to the above conversion factors to credit (or debit) the diesel vehicle fuel economy for process energy savings (or penalties) should also be made. The savings in real energy to the nation would vary directly with the actual ratio of diesel to gasoline fuel production and indirectly with the sales or production mix of diesel and gasoline fueled vehicles. Therefore, several options for factoring energy process savings (or penalties) into the conversion factor exist.

(1) Adjust the conversion factor for process energy savings on an annual basis to reflect actual shifts in diesel/gasoline consumption caused by shifts in diesel/gasoline vehicle sales using calendar year 1975 as the base year to calculate savings.

(2) Predict the ultimate or equilibrium saturation of the in-use automotive fleet market by the diesel fueled vehicle and calculate the process savings from the resultant saturation ratio of diesel to gasoline fuels production using 1975 as the base year to calculate the savings. For example, if diesel sales are projected to saturate at 25% of annual automotive sales the equilibrium ratio of diesel/gasoline fuel consumption can be derived and energy savings calculated.

(3) Assume that the ratio of diesel fuel to gasoline production that represents the maximum process energy savings is a desirable national goal and calculate the conversion factor on basis of the maximum process energy savings relative to the 1975 base year. In this case, the Exxon study predicts that the maximum savings is 2% with an optimum ratio of 55:45 diesel/gasoline production.

This study is intended to treat only the technical issues but the selection of the appropriate option from the above could be dictated by the legal interpretation of the requirement of the Energy Policy and Conservation Act - that is, should the conversion factor be based on real savings from the actual sales of diesel vehicles or should it be based upon potentially realizeable savings in the long term. In the former case option 1 would be appropriate whereas in the latter case options 2 and 3 might be appropriate.

Another important consideration in the treatment of the energy savings is the issue of how to allocate the process energy savings among the products of the refinery.

One obvious way is to allocate the savings among all of the products. If S is the % savings in process energy the savings factor basically becomes

*If not adjusted for the differences in heat content per unit volume diesel mpg values will be inflated relative to gasoline. This is because more gallons of gasoline can be produced from the same amount of crude oil (neglecting process energy requirements for the moment); thus, the need to adjust on a common Btu-basis.

$$\frac{1}{1 - S/100}$$

However, it is reasonable to argue that since the automotive fuels sector creates all of the savings it should receive all of the savings as a credit exclusively to the automotive fuels account. The factor would then be adjusted by the fraction f_x, of refinery product represented by the automotive fuels account. The savings factor would be

$$\frac{1}{1 - S/_{100f_x}}$$

The manufacturers of diesel-fueled vehicles might argue further refinements. If the diesel fueled vehicle generates the process energy savings then the entire savings should be allocated to the diesel fuel account. If f_D is the fraction of diesel fuel production the savings becomes

$$\frac{1}{1 - S/_{100f_D}}$$

Finally, the passenger diesel car manufacturer might argue that it is the diesel car that generates the process savings so all of the savings should be allocated to the passenger car diesel fuel account. Again if F_{AD} is the fraction of passenger car automotive fuel assumption the savings becomes

$$\frac{1}{1 - \frac{S}{100}F_{AD}}$$

The numerical differences between the methods of allocation can be illustrated by considering the case from the Exxon study where the maximum process energy savings is achieved. In this case, S = 2%, f_x = 0.50, f_D = 0.50 X 0.55, and f_{AD} = 0.50 X 0.55 X .45/.55 since 2% maximum process savings is achieved, automotive fuels accounts for 50% of total refinery product, diesel fuel for 55% of the automotive fuel, and diesel fuel for trucks accounts for 10% of the automotive fuel. Thus, the factors become

Case	Factor
1. Allocation amongst all products	1.02
2. Allocation to automotive fuels	1.04
3. Allocation to all diesel fuels	1.08
4. Allocation to only passenger car diesel fuels	1.10

In this study the method allocating the process savings to the total diesel fuel account (truck and auto) was selected primarily because the actual savings accrues from both truck and passenger car diesel usage.* Further, diesel trucks also contribute to process energy savings as they displace gasoline truck counterparts. Also it might be difficult in the future to accurately separate diesel fuel sales between trucks and cars as they would likely be fueled by the same fuel dispensers. Currently, the bulk of truck fuel is dispensed by separate fuel pumps which provides a check against statistical methods of predicting truck fuel usage.

Unfortunately, from the standpoint of this study projections of future diesel vehicle sales are non-existent or at least they were unknown to the study, therefore meaningful computations for options one and two were not possible. Therefore, illustrative computations were performed for three cases, a scenario for option 3, a scenario where it is arbitrarily assumed that in the mid-term (5-10 years) automotive diesel fuel consumption would reach 20% of the total automotive fuel consumption and a near-term (0-5 years) where automotive diesel fuel consumption gains 1% at the expense of gasoline.

The methodology and computations are described in appendix II. For the cases the calculations produced the following conversion factors:

Case I - Maximum process energy savings

Mpg (Indolene HO III equivalent) = 0.976 x Mph Diesel #1
Mpg (Indolene HO III equivalent) = 0.942 x Mph Diesel #2

Case II - Automotive Diesel Equal to 20% of total automotive fuel

Mpg (Indolene HO III equivalent) = 0.943 x Mpg Diesel #1
Mpg (Indolene HO III equivalent) = 0.909 x Mpg Diesel #2

Case III - Automotive Diesel Increases Market Share by 1%

Mpg (Indolene HO III equivalent) = 0.912 x Mpg (Diesel #1)
Mpg (Indolene HO III equivalent) = 0.880 x Mpg (Diesel #2)

Discussion

Table one summarizes all of the computations. For the first two cases computed above significant differences in the conversion factors result when energy savings are considered. However, these cases also represent significant numbers of diesel vehicles in the automotive vehicle population. The savings in Case III produces only a marginal change in conversion factor. At the present time it is estimated that

*In this study consumption of heating oils and Jet fuels was assumed to remain constant. In reality significant shifts in either of these markets could significantly impact on the energy savings. A point could be reached where the combined usage of middle distillate fuels could produce a penalty in process energy for further increases in diesel vehicle population.

Table I. Summary of Computations

Fuel	Case	Factor Heating Value Diff Only	Factor Energy Savings Only	Total Factor
Diesel #1	I	0.905	1.079	0.976
	II	0.905	1.042	0.943
	III	0.905	1.008	0.912
Diesel #2	I	0.973	1.079	0.942
	II	0.873	1.042	0.909
	III	0.873	1.008	0.880

there are about 100,000 diesel-powered automobiles compared to about 110,000,000 gasoline-powered automobiles. Thus, to reach the ratios of diesel fuel to gasoline fuel consumption for the first two cases considered would require replacement of greater than 55,000,000 gasoline vehicles in the current fleet for the maximum energy savings and about 10 -15,000,000 gasoline automobiles for Case II. Clearly, while diesel-powered vehicle sales are expected to escalate in 1977 - 1978 (if for example VW and GM introduce diesel vehicles) the proportions of diesel/gasoline fuel usage used in the Cases I, II will not be reached in the next five years. Case III while still optimistic shows that energy savings will be marginal in the foreseeable future.

Also it should be noted that the conversion factors will be utilized only to calculate a manufacturer's average fuel economy but consumer labels for the diesel-fueled vehicles will bear actual mileage in terms of diesel fuel.

Recommendation

Until a legal clarification is obtained it is assumed that the Energy Policy and Conservation Act requires that real (as opposed to projected) energy conversion factors be utilized. Since the conversion factors will be used only by DOT/EPA to compute a manufacturer's average fuel economy and since the current diesel population is too small to calculate meaningful process energy savings, it is recommended that a conversion factor based only on differences in heating values be utilized in the near-term.

In the longer term, the actual production records together with certification applications will permit more accurate projections of diesel sales and it is recommended that the conversion factors be then revised annually reflecting both heating value differences and process energy savings.

Appendix I

Computation of Diesel Fuel Equivalence to Gasoline Reflecting Only Differences in Heat Content

If the fuel economies (mpg) of automobiles powered by gasoline or diesel engines are considered proportional to the Btu's/gal of the corresponding fuels, the following expression could be written:

$$\frac{mpg_{(gasoline)}}{mpg_{(diesel)}} = \frac{Btu/gal_{(gasoline)}}{Btu/gal_{(diesel)}}$$

For the average specifications of the gasoline and diesel fuels used during the FTP for automobiles, this ratio has the following values:

$$\frac{mpg_{(Indolene\ HO\ III)}}{mpg_{(Diesel\ D\text{-}1)}} = \frac{114{,}107}{126{,}100} = 0.905$$

$$\frac{mpg_{(Indolene\ HO\ III)}}{mpg_{(Diesel\ D\text{-}2)}} = \frac{114{,}107}{130{,}650} = 0.873$$

The net heat contents of the fuels have been determined as indicated below.

Net heat content of Indolene HO III

The EPA Certification Division uses σ, gasoline density, = 6.167 lb/gal for exhaust emission computations.

Accordingly, specific gravity, S.G. = 6.167/8.330 = 0.740

and API gravity = $\frac{141.5}{S.G. = 0.740} - 131.5 = 59.7.$

The SAE paper 740522 indicates that "The following correlation for heat content is quite accurate because it is based on a large volume of data obtained by the CRC, the Bureau of Mines, and the API:

Low Heating Value, LHV = 16.24G - 3.007A + (I)

0.01714GV - 0.2983AG + 0.00053GAV + 17,685

where:

G = API gravity

V = Average of 10,50 and 90% distillation points
A = Aromatics content, %."

Now, the average values for Indolene HO III are:

$$G = 59.7$$

$$V = (124.5 + 218.5 + 312.5)/3 = 218.5^{o}F$$

$$A = 27\% \text{ aromatics.}$$

Therefore, substituting these values in equation (I) we get:

LHV = 18,503 Btu/lb.,

or for σ = 6.167 lb/gal.

LHV = 114,197 Btu/gal.

Net heat content of diesel fuel D-1

According to the EPA specifications, this fuel has on the average:

API gravity: 42
50% distillation: $445^{o}F$

Then, from the chart in Figure 4 of the SAE Standard J1082, we get

LHV = 126,100 Btu/gal.

Net heat content of diesel fuel D-2

According to the EPA specifications, this fuel has on the average:

API gravity: 35
50% distillation: $505^{o}F$

Then, from the chart in Figure 4 of the SAE Standard J1082, we get

LHV = 130,650 Btu/gal.

Appendix II

Methodology and Computation of Diesel Fuel Equivalence to Gasoline Reflecting Heat Content Differences and Process Energy Savings

Nomenclature

Let E_D = Total btu's of diesel fuel product,
E_G = Total btu's of gasoline fuel product
H_D = heat of combustion of diesel fuel, Btu/gal
H_G = heat of combustion of gasoline fuel, Btu/gal
s = process energy savings, %
S = process energy savings, Btu
f = fraction of automotive fuel product produced by refinery
f_D = fraction of automotive diesel fuel produced from refinery
Superscript = baseline value.

Assumptions

(1) From Exxon Study process energy savings, s, is a function of the ratio of diesel fuel production to total automotive fuel production, $E_D/(E_D + E_G)$, and is given in figure 1.

(2) All process energy savings are credited to automotive fuel production and specifically to the diesel fuel account.

(3) The fraction of automotive fuel consumption, f, is assumed to be 0.50 (actually it is currently 0.60 because domestic production of heavy heating oils is negligible, but if imports are ceased the fraction would be closer to 0.50).

(4) For the baseline, the ratio of diesel fuel production to gasoline production is assumed to be 10/90. Almost all of this diesel fuel is currently consumed by truck diesels. For the methodology truck consumption is assumed to remain a constant % of distillate fuels.

Methodology

Process Energy Savings, S, $= \frac{s}{100f} (E'_D + E'_G)$

Diesel to Gasoline Equivalence Factor = F

$$F = \frac{H_G}{H_D} \frac{E_D}{(E_D - S)}$$

$$F = \frac{H_G}{H_D\ (1 - S/E_D)}$$

$$F = \frac{H_G/H_D}{1 - \frac{s}{100f}\frac{(E'_D + E'_G/E_D)}{E_D}}$$

If it is assumed that $(E'_D + E'_G) = (E_D + E_G)$ the equation simplifies to

$$F = \frac{H_G/H_D}{1 - S/100\ f_D}$$

where $$f_D = \frac{f\ \ E_D}{(E_D + E_G)}$$

Calculations

Three cases are calculated; Case I assumes the maximum process energy savings is achieved, Case II assumes diesel fuel production for automotive saturates at 20% of total automotive production, and Case III assumes diesel fuel production displaces gasoline by 1%.

Case I

s = 2% from Exxon study, fig. 1
f = 0.50
E_D/E_G = 0.55/0.45 from Exxon Study
H_G/H_D = 0.873 for diesel #2 from appendix 1.

$$F = \frac{H_G/H_D}{1 - \frac{S}{100f_D}}$$

$$F = \frac{0.873}{1 - \frac{0.02}{(0.5)(0.55)}}$$

$$F = \frac{0.873}{0.927}$$

$$F = 0.942$$

Case II

s = 0.4% from Exxon Study, fig. 1
f = 0.50
E_D/E_G = 0.20/.80
H_G/H_D = 0.873 for diesel #2 from appendix 1.

$$F = \frac{H_G/H_D}{1 - \frac{s}{100f_D}}$$

$$= \frac{.873}{1 - \frac{0.004}{(.4)(.2)}}$$

$$= \frac{.873}{0.960} = .909$$

Case III

S = 0.044% from figure 1, Exxon Study
E_D/E_G = 0.11/.89
H_G/H_D = 0.873 for Diesel #2 from Appendix 1.

$$F = \frac{H_G/H_D}{1 - \frac{s}{100f_D}}$$

$$= \frac{0.873}{(.00044)/(.5)(0.11)}$$

$$= \frac{0.873}{0.992} = 0.880$$

Similarly the calculations for diesel #1 are

Case I

$$F = \frac{.905}{.927} = .976$$

Case II

$$F = \frac{.905}{.960} = 0.943$$

Case III

$$F = \frac{.905}{.992} = 0.912$$