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Vehicle Efficiency - Road vs Dynamometer

by

Bruce Grugett

NOTICE

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

I. Introduction

The accuracy of results obtained from vehicle fuel consumption measurements performed on a dynamometer in predicting fuel consumption on the road depends upon the ability of the dynamometer to simulate the road experience of the vehicle. A previous study[1] indicated that vehicles consume less fuel (higher mpg) in a test run on the current EPA dynamometer than when the same test is performed on the road. This implies that in current dynamometer testing either fuel consumption is not measured accurately, too little work is extracted from the vehicle, or the vehicle operates more efficiently than on the road.

II. Background

In a program begun last summer and recently completed, a series of steady-state tests were run on a 1976 Mercury Montego on a twin-roll dynamometer at the EPA and on the Transportation Research Center test track in Ohio. During these tests measured fuel consumption was manually recorded while wheel torque and vehicle speed were recorded on magnetic tape.

This is the first time that EPA has conducted an experimental program in which vehicle torque and speed measurements were obtained during a test in which fuel consumption was measured. These additional data are sufficient to calculate the work done by the vehicle which can then be divided by the fuel consumed to give a measure of vehicle efficiency.

III. Measurements

The data discussed in this report were all obtained from steady state measurements on the test track of the Transportation Research Center of Ohio or from dynamometer measurements at the EPA MVEL laboratory. The data consisted of two general categories, measurements of the fuel consumed by the vehicle and measurements of the energy expended by the vehicle during the period of the fuel consumption measurement.

A. Fuel Consumed

All fuel consumption data were obtained by a Fluidyne 1240 flow meter. For both the road and the dynamometer, the measured fuel consumption was corrected to fuel volume at the common reference temperature of 60°F. This corrected fuel consumption was used throughout the report when calculating vehicle efficiency on both the road and dynamometer.

B. Energy Expended

The work done by the vehicle can be obtained by integrating the instantaneous power, given by the product of the wheel torque and velocity, over the time of the test. The torque was measured with torque transducers mounted on the wheels, so the torque values include the torque exerted by the wheels on the tires. Since the tires are "downstream" of the torque sensors, tire losses are included in the data. Losses "upstream" of the torque sensor, for example engine and drive train losses are not included.

The energy expended is the true integral of the power delivered to the rear wheels. The instantaneous power is given by the product of the torque and angular velocity.

$$P_i = T_i W_i \quad (1)$$

Where:

P_i = the instantaneous power at the i^{th} sample period.

T_i = the instantaneous torque at the i^{th} sample period.

W_i = the instantaneous angular velocity at the i^{th} sample period.

The energy expended in any period is the product of the power transmitted times the timed interval. In this test program the time periods between the data samples were always one second. Therefore, the total energy expended during the test is, to a very close approximation, simply the sum of the observed powers. That is:

$$E = \sum_i P_i \Delta t_i$$

$$= \Delta t \Sigma T_i W_i \quad (2)$$

Where:

E = the total energy expended during the test.

Δt = the interval between data samples

= one second

Equation (2) was used to calculate the energy expended over each road and dynamometer test. In all calculations the true angular velocities of the drive wheels, as measured by pulse encoders on the wheels, were used.

IV. Discussion

In order to better compare the fuel measurements and energy calculations from the different tests, a specific fuel consumption and specific energy expended were calculated by dividing the total energy and the total fuel consumed by the distance travelled during the test. That is:

$$e = E/d$$

and

$$f = F/d$$

Where:

E = Total energy expended.
F = Total fuel consumed.

e = the specific energy expended (Joule/M)

f = the specific fuel consumption (cc/km)

d = the test distance

All of the data, for both the track and the dynamometer tests are presented in the appendix and are plotted in Figure 1. There are two very significant observations which can be made from this figure; the linearity and repeatability of the dynamometer data, and the large difference between road and the dynamometer data.

A. Dynamometer Data

The dynamometer data appear to represent a linear relationship between the fuel consumed and the energy extracted. A linear regression of these data resulted in a correlation coefficient of .97; that is 94 percent ($R^2 = 97^2 = .94$) of the variation of the data may be explained by the linear relation.

The linearity is surprising since the data vary over a ± 16 percent range in fuel consumption and a factor of two in expended energy. These data include tests at three different speeds, 40, 50, and 55 mph, and three different dynamometer adjustments. The important point is that the actual energy expended was measured during each test. The vehicle fuel consumption appears to vary linearly with the energy expended over a wide range of both parameters.

B. Road versus Dynamometer Results

The second significant observation is the large difference between the vehicle fuel consumption on the road and on the dynamometer. While this is apparent from Figure 1, it is even more evident when the difference in the engine efficiency on the road versus that on the dynamometer is considered.

The efficiency of any system is defined to be the ratio of the useful energy extracted from the system to the energy put into the system. In this case the useful energy extracted from a vehicle is the mechanical work done by the wheels while the input energy is the chemical energy in the fuel. The efficiency can also be expressed as a percentage if the amount of chemical potential energy contained in the fuel is known. D.E. Foreiger reports in his paper "Gasoline Factors Affecting Fuel Economy," (2) that the energy obtained from burning commercially available gasoline falls in a narrow range around 115,000 BTU/gallon, or equivalently 32023 J/cc.

The vehicle efficiencies were calculated for each of the 50 mi/hr steady-state tests on the road and on the dynamometer. On the road, the vehicle produced an average of 3,612 joules per cubic centimeter (J/cc) of fuel used. This gives a vehicle efficiency on the road of 11.3 percent. On the dynamometer, however, the average efficiency was 5430 J/cc or 17.0 percent. These results are shown in the following table.

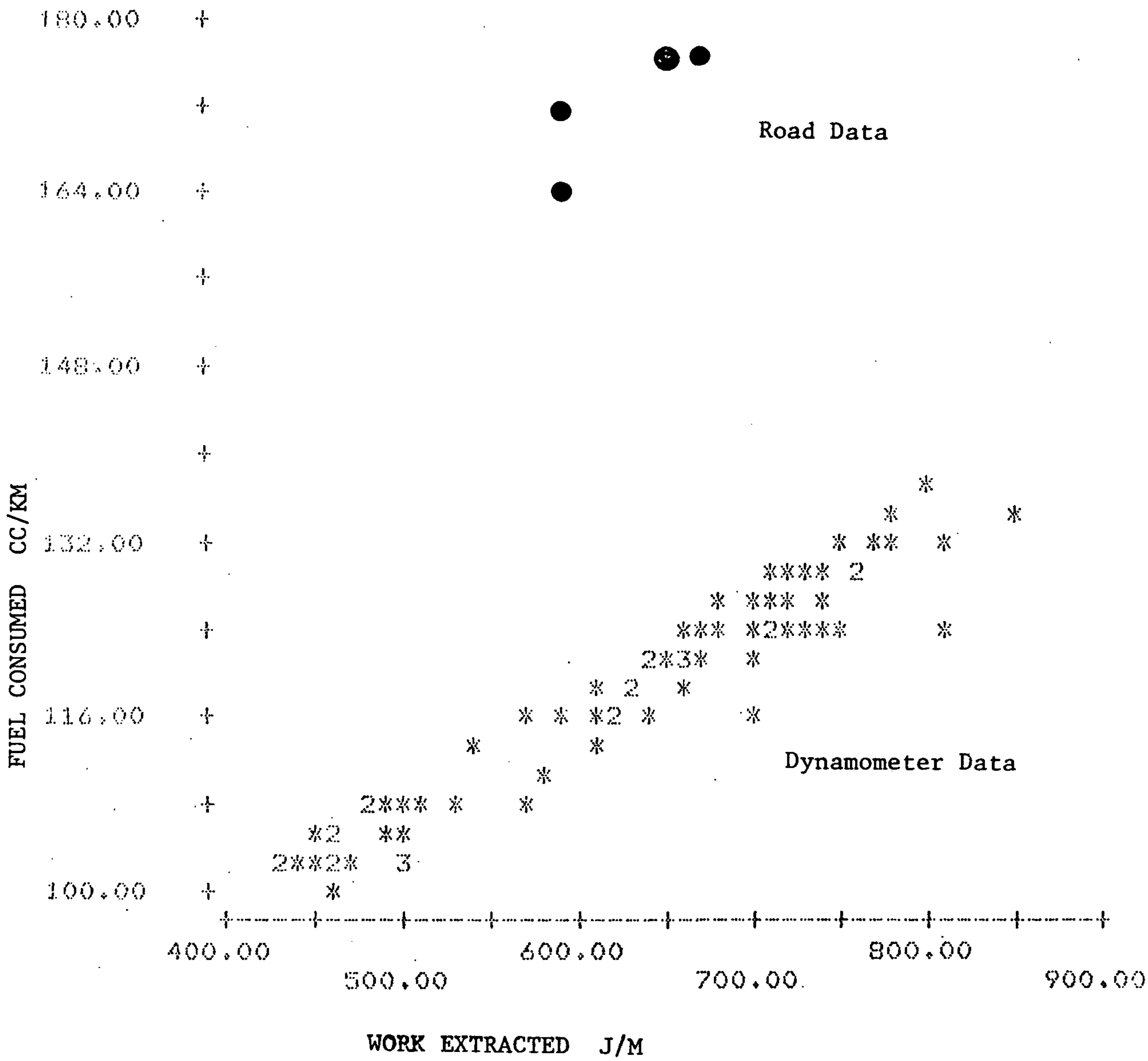
180.00
164.00
148.00
132.00
116.00
100.00
FUEL CONSUMED CC/KM
Road Data
Dynamometer Data
400.00
500.00
600.00
700.00
800.00
900.00
WORK EXTRACTED J/M

FIGURE 1.

Vehicle Efficiency

	J/cc	Percent
Road	3612	11.3
Dyno.	5430	17.0
Difference	1822	6.3

These differences appear quite large. Compared to the results on the dynamometer, the vehicle consumed 34% more fuel on the road for the same amount of work. A statistical "t-test" confirmed this observation, showing that there is greater than 99% confidence that the dynamometer efficiency was greater than the road. Since the differences are so large, and the statistical tests confirmed that these are not random fluctuations, the possibility of systematic experimental errors was investigated. Errors in either the fuel consumption measurements or errors in the torque or speed measurements could result in the observed differences between the road and the dynamometer efficiencies.

It is unlikely that the difference in efficiency is due to an error in measuring fuel consumption. The flow meter was calibrated before the test program and the calibration was confirmed during the program. In any case the same instrument was used for both the road and dynamometer tests. Even if the calibration was somewhat in error, the same error would be present in both the road dynamometer measurements, therefore this could not explain the difference between the road and dynamometer results.

The dynamometer fuel consumption data were approximately confirmed by carbon balance measurements, therefore if any error exists in the flow meter data it would have to be the road data which is in error. There is, however, no evidience of error in these data. All of the steady-state data are in approximate agreement with any data variability much less than the difference between the road and the dynamometer results.

In the case of the torque measurements, some thermal drift problems were reported in the course of the track measurements. Therefore, as a check on both the torque and speed measurements, road coastdown times were used as an independent estimate of the energy required by the vehicle per unit distance traveled. In this case, the average force exerted by the vehicle at 50 mi/hr was calculated from the coastdown conducted immediately after each steady-state test. This force was assumed to be the average work done by the vehicle per unit distance travelled during the preceeding 50 mi/hr steady-state test. This coastdown derived force was then divided by the fuel consumed per unit distance to give an estimate of vehicle efficiency. The efficiencies computed in this manner were 13.1 percent for the road and 19.2 percent for the dynamometer. Although the magnitudes of these numbers are slightly different than those obtained directly using the torque and speed data, they are quite similar and they indicate the same difference in the vehicle efficiency on the road versus that on the dynamometer.

It should be noted that the vehicle speed measurements used to calculate the work done and the fuel consumed per unit distance were slightly different for the dynamometer and the road. The road velocity was obtained from a fifth wheel, while the velocity during dynamometer operation was obtained from the dynamometer rear roll. A recent EPA study (3) concludes that the dynamometer rear roll velocity overestimates the road velocity of the vehicle which would occur for the same vehicle drive wheel conditions. The net effect of correcting the data of this report would be to shift all of the dynamometer data of Figure 1 both upward and to the right. The total relationship between the road and dynamometer data would change very little, since; in any case the effect is only 1 to 2%. The effect of an error in velocity is minimal with the methodology used to analyze the data of this report since the energy extracted from the vehicle was directly measured. In addition, when computing the efficiencies, any systematic errors in the vehicle velocity or simulated velocity would be self compensating and no error would be introduced in the efficiency.

No significant systematic errors could be identified in the measurements, therefore, attempts were made to identify differences in the vehicle state or condition between the road and dynamometer tests.

Engine efficiency can vary with loading. On the dynamometer, 50 mi/hr steady-state tests were run with power absorber settings of 10.4, 11.4, and 12.4 horsepower. The data in the table below confirms the fact that in the normal operating range, engine efficiency, as previously calculated, increases with load.

Power Absorber Setting (HP)	J/cc	Percent Efficiency
10.4	5148	16.1
11.4	5346	16.7
12.4	5459	17.0

It could be hypothesized that the higher efficiencies observed on the dynamometer resulted from greater vehicle loading on the dynamometer than on the road. However, the actual power at the rear wheels was measured and no increase in loading was observed. In addition, increased load would result in increased fuel consumption and exactly the opposite was observed.

Throughout the efficiency calculations the energy available at the rear wheels was used as the measure of useful work. Any changes in energy dissipation between the engine and the drive wheels would affect the fuel consumption for the same resultant energy at the wheels, thereby affecting the calculated efficiency.

It could be hypothesized, for example, that the track to dynamometer differences could be a result of severe drive wheel brake drag during the track measurements. However, this would have been observed in the vehicle coastdowns. As discussed earlier, the coastdown measurements were in reasonable agreement with the torque wheel data.

Part of the lower efficiency on the road can be accounted for by the fact that during tests on the road, electrical power for the test equipment used was taken from the vehicle, while during dynamometer testing it was not. The inverter used on the road to change the 12-volt DC level into an AC supply for the test equipment is capable of outputting 200 watts. At a 50 mph steady-state, this is an additional unaccounted load of about 10 J/m. Considering Figure 1, this would have the effect of shifting the road data to the right by 10 J/m. This is in the right direction, but inadequate to explain more than a small fraction of the observed differences. Even if very poor efficiencies are assumed for the vehicle alternator and the inverter and the data were shifted 50 J/m this cannot explain the observed differences.

In a similar manner, the power steering of the vehicle would contribute to the greater fuel consumption on the road. Again, however, this effect is not sufficient to explain an appreciable part of the observed differences, especially since the test track was a very large (7.5 mi) oval.

The differential probably dissipated a different amount of energy on the road than on the dynamometer. This would occur since the road measurements were obtained at lower ambient temperature and because very little cooling air is supplied to the differential when the vehicle is operated on the dynamometer. In general, it seems likely that the differential operates at higher temperatures on the dynamometer than on the road. This would reduce the lubricant viscosity and could have a significant effect on the energy dissipation of the differential and hence affect the efficiency. Earlier dynamometer experiments have indicated that on the dynamometer the differential consumes approximately 1000 watts at 50 mi/hr (4). This is only 50 J/m therefore, even if the differential losses doubled or tripled on the road this would not explain the differences observed between the road and dynamometer results. In addition differential effects would have been observed during the vehicle coastdowns.

It seems impossible to explain the observed fuel consumption differences by any mechanism which affects the load imposed on the engine. The most plausible explanation is that the differences were caused by a direct temperature effect on the engine. The road tests were conducted with the ambient temperature in the range of 52-67°F, while the dynamometer tests were conducted in the range of 71-76°F. If the vehicle engine operated under much richer fuel-air conditions at the lower temperature, then this might explain the large observed difference. The enrichment might occur either intentionally, or by malfunction, such as a sticking automatic choke.

V. Conclusions

Two important conclusions can be reached from the reported data.

The fuel consumed during these measurements was linerly related to the measured energy extracted from the vehicle. Second, a significant difference was observed between the fuel consumed by the vehicle on the road and that consumed by the vehicle on the dynamometer when the same energy was extracted from the vehicle.

A. Linearity of the Fuel Consumption Data

The observation that more fuel is burned as more work in extracted from the vehicle is inherently logical. The surprising observation is that, in this experiment, strong linearity was observed over a wide range of vehicle work. This implies that it should be possible to easily, and accurately predict the fuel economy effects of many parameters. For example, if the energy required to operate an air conditioner or other assessory is known, then the resulting fuel consumption effect could be easily and accurately predicted. Similarly, the fuel consumption effects of changes in driving cycles could be predicted from the energy demand of the driving cycle, if vehicle performances are known for similar cycles.

B. Track versus Dynamometer

It is concluded that, under the conditions of this experiment significantly different fuel consumption was measured on the track versus the consumption measured on the dynamometer. It has been reported (5) that temperature does affect fuel economy, but reported temerpature effects are not large enough to account for the efficiency differences which were observed, Differences in vehicle assessory loading and temperature effects on the drive train can account for some of the track to dynamometer difference, but not the majority of the effect. It must, therefore, be concluded that either the road fuel consumption data are in error, or that a very significant temperature realted effect occurred during the track measurements. No evidence of error in the road fuel consumption data could be detected. If the observed effect was temperature induced it might be very vehicle specific such as extreme choke action and therefore be difficult to confirm.

VI. Recommendations

The conclusions of this report are somewhat surprising; therefore, the first recommendation is that these results be confirmed. Since in general, ambient temperature may be a direct or indirect cause of vehicle fuel economy differences between track and dynamometer measurements, temperatures of vehicle components should be monitored in future programs. These programs should also attempt to quantify the energy demand and fuel consumption effects of various accessories and drivetrain components.

In this test program all parameters, except track fuel consumption, were confirmed by some redundant measurement. For example the wheel torque data were confirmed by the coastdown results. In any future program it is recommended that some confirmatory measurement of the track fuel consumption be made. Even the simple recording of odometer readings and tank fills would provide some confirmatory data.

References

1. J. Dillard, Murrell, Previews of Dyno vs. Track Fuel Economy Findings, EPA memo to John P. DeKany, August 3, 1977.

2. D.E. Foringer, "Gasoline Factors Affecting Fuel Economy," SAE Paper No. 650427.

3. J. Yurko, "A Track to Twin Roll Dynamometer Comparision of Several Different Methods of Vehicle Velocity Simulation," EPA Technical Report to be released.

4. R. W. Burgeson, "Tire Test Variability," EPA Technical Report, March 1978.

5. A.C.S. Hayden, "The Effect of Technology on Automobile Fuel Economy under Canadian Conditions," SAE 780935, 1978.

Appendix

Dynamometer Efficiency

Fuel Consumed cc/km	Energy Extracted J/M
122	638
106	495
128	739
123	684
108	511
130	760
116	607
103	456
122	669
125	735
109	568
135	853
129	733
112	541
123	657
107	487
132	754
103	504
124	746
118	663
126	739
111	582
114	606
101	457
121	700
117	622
103	462
124	713
105	453
127	710
115	573
103	430
122	664
124	674
106	493
132	779
120	637
105	460
128	720
126	679
108	483
135	778
118	629
103	471
123	721
119	630

Dynamometer Efficiency (cont.)

Fuel Consumed cc/km	Energy Extracted J/M
104	462
127	720
116	618
103	453
124	704
122	647
107	476
131	765
117	702
103	503
125	810
118	610
103	453
128	706
124	708
109	529
133	807
126	700
136	804
115	589
103	434
122	662
121	663
107	495
129	756
115	635
103	495
124	725
171	586
177	673
164	59[illegible]
178	646

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