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Technical Report

An Investigation of the Fuel Economy Effects of Tire Related Parameters

by

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Abstract

A program was conducted on a test track to determine the fuel consumption effects of radial vs. bias-ply tires, two radial tires from different manufacturers, and increased tire pressure. The program was designed to eliminate ambient effects by running two identical test vehicles simultaneously and alternating the parameter of interest between the two vehicles. Five different tire types were used (including the original equipment manufacturer tires from the vehicles).

This study demonstrated that radial tires were six percent more fuel efficient than bias-ply tires; the radial tires from one manufacturer were four percent more fuel efficient than radial tires from a different manufacturer; and radial tires inflated to 28 psig were three percent more fuel efficient than radial tires inflated to 20 psig. This program also determined that laboratory measurements of rolling resistance are good predictors of track fuel consumption.

I. Introduction

Vehicle fuel economy is an area of significant present concern. Therefore, it was decided that the fuel economy effects of tire construction type, variations among tires of the same type, and tire inflation pressure, should be investigated. This report describes the experimental programs used in this study and presents the fuel economy effects of these parameters for vehicles operated over the EPA city and highway test cycles.

II. Background

It is well known that tires can affect the fuel economy of a vehicle, most notably the fuel efficiency of radial tires. 1,2,3/ In addition, fuel economy effects have been attributed to variations among tires of the same construction type and to inflation pressure. However in some cases, such as pressure effects, the literature contains little data from direct observation; rather, the fuel economy effects have been inferred from other data. 3/ In other cases the only reported data were obtained during vehicle operation at steady speeds. While these data correctly indicate the presence and direction of an effect, the steady state results may not reflect the magnitude of the fuel conservation which would be achieved under typical vehicle operating conditions.

An experiment was proposed to determine transient cycle fuel economy effects of tire construction, that is, radial versus bias and the effects of the differences between two types of radial tires. This study also investigated the effects of tire inflation pressure. For this program, the EPA urban and highway cycles were chosen as representative of typical vehicle operation in metropolitan and rural areas, respectively. All testing was conducted on an oval test track at the Transportation Research Center of Ohio.

III. Experimental Design

The purpose of this experiment was to investigate the fuel economy effects of tires and tire pressure. In general, these effects are relatively small, less than 5 percent. Since typical variability of fuel economy measurements may be of this magnitude, it was considered important to carefully design the experiment.

Table 1, which is based on one-tailed t-statistic tests, is the basis of the experimental design. This table presents the approximate number of observations necessary to resolve differences between the means of two sets of experimental observations with various observed standard deviations. For example, row 5 of this table demonstrates that if the mean of the experimental data set one, is greater than the mean of the data set two by 0.2, and the standard deviations of the data sets are 0.2, then if 3 observations occurred in each set there is 90% confidence that the mean of set one is larger than the mean of set two.

Experimental data and theoretical investigations provide sufficient basis for estimation of the magnitude of the effects anticipated. Different tire construction types will effect vehicle fuel economy by about 0.4 mpg or more. Variations among a single tire type probably induce fuel economy effects of 0.2 to 0.4 mpg, and change in tire inflation pressures of the order of 5 psi probably change fuel economy by 0.2 to 0.3 mpg.

Table 1

Δx (fuel economy effect)	s (experimental standard deviation)	Number of observations required at confidence levels 90%	95%	99%
	0.3	30	49	98
0.1	0.2	13	22	43
	0.1	3	5	11
	0.3	7	12	24
0.2	0.2	3	5	11
	0.1	1	2	3
	0.3	4	6	11
0.3	0.2	2	3	6
	0.1	1	1	2
	0.3	2	3	6
0.4	0.2	1	2	3
	0.1	1	1	1

EPA track fuel economy measurements from the test programs conducted during the summer of 1978 provided test variability estimates which indicated observed standard deviations of 0.3 to 0.2 mpg.

The magnitudes of the anticipated effects and the expected test variability in conjunction with Table 1 indicate immediate potential test program problems. Only the effects of tire construction should be readily apparent. Consistent with this observation, these effects are the only ones for which transient cycle results have been reported in the literature. Pressure effects and the effects of variations among tires of the same generic type are probably observable with a small number of tests, but the confidence would be low. In addition it must be remembered that these confidence levels are only for the test that the mean of one set of observations is greater than mean of the other set, and are not confidence levels on the magnitudes of the effect. Clearly, to accurately identify the magnitude of the anticipated effects in the presence of the anticipated variability requires an extensive number of repeat tests.

The only alternative to time consuming, and hence expensive repetitive testing is to try to reduce the measurement variability. This has very good potential since, for a given level of confidence, the number of tests required are proportional to the square of the experimental standard deviation.

It is hypothesized that variations in ambient conditions are responsible for much of the observed track fuel economy variability. This is logical since ambient conditions affect the fuel economy of a vehicle through several mechanisms. For example, temperature affects the tire rolling resistance directly. Indirectly it has an effect on the aerodynamic drag forces by changing the air density. In addition, temperature affects the vehicle engine by changing the fuel-air ratio of the combustion charge, and also has an effect on the thermodynamic efficiency of the engine.

Unfortunately it is impossible to control the test ambient conditions for a large track. The alternative of only testing in a narrow, acceptable, "ambient window" is also undesirable since this tends to make the test program very long and arduous, at least in calendar time.

The approach of using two identical test vehicles was proposed as a possible solution to the potential test problems of the program. The accepted proposal was to simultaneously operate two vehicles, identical except for the parameter under observation, in as similar a manner as possible. The investigated parameter would then be changed so that vehicle one would be in the previous test configuration of vehicle two, and vice versa for vehicle two. The test would then be repeated under these vehicle configuration conditions. Test pairs can be repeated until acceptable confidence is obtained, either for effect of the investigated parameter or for the lack of effect.

The major advantage of this approach is that the effects of ambient parameters, such as temperature and wind, should be minimized. The assumption is that ambient changes will affect both vehicles in approximately the same manner, eliminating observation of the "first order" ambient effects. This allows testing over a wide ambient window, such as a 20°C temperature range while observing little of the ambient effects in the paired data. This was expected to provide good experimental precision and to allow completion of the project in a reasonable calendar time.

The disadvantages of the experimental plan is that two vehicles, two sets of most instrumentation, and two vehicle operator teams are required. In addition, failure of either instrumentation set eliminates the paired data point, hence the design is twice as vulnerable to the probability of random equipment failure as would be a single vehicle test program.

IV. The Experimental Program

The parameters investigated were tire construction type, variations among tires of the same type, and tire inflation pressure. For each investigated parameter the intent was to monitor the data as collected and to only collect sufficient data to define the effects of the parameter to within about $\pm$ 0.5cc/km (approximately $\pm$0.1 mpg for a 20 mpg vehicle). The goal was to have 90% or higher confidence in these results, or conversely, to have at least 90% confidence that the effect was less than 0.5cc/km.

It was decided to investigate the parameters in the order of decreasing anticipated effects, as this would maximize the probability that a maximum number of the desired parameters could be investigated within possible constraints of weather, available test time, or costs.

The specific parameters chosen for investigation, and the order of investigation was:

A. "Average" radial tires versus "average" bias-ply tires.

B. "Good" radial tires versus "poor" radial tires.

C. 28 psig versus 20 psig (4 psig above the recommended inflation and 4 psig below recommended pressure).

The identical test vehicles, Vehicle 1 and Vehicle 2, were 1979 Chevrolet Novas equipped with 2.3L engines, 1 bbl carburetors, and three speed automatic transmissions. The instruments used for measuring fuel consumption over the EPA cycles included a Fluidyne Model 1240T fuel flow meter, a Nucleus 5th wheel with distance readout, and a Hewlett-Packard chart recorder. Power was supplied to the recorder from a 125 VA inverter. In addition, each vehicle was equipped with a Fluke frequency counter which measured driveshaft revolutions over a reference distance. Driveshaft revolution measurements served as a check that fuel consumption differences were not due to changes in N/V ratio. The tires selected for the program are listed below:

Tire	Rolling Resistance Coefficient	Diameter (mm)
P195/75 R14 ("Good" Radial)	0.0099	648
P195/75 R14 ("Average" Radial)	0.0104	648
P205/70 R14 ("Poor" Radial)	0.0122	649
E78x14 (Bias-ply)	0.0144	663

The tires were obtained from the General Motors Milford Proving Grounds and were selected on the basis of rolling resistance measurements conducted by GM using the SAE proposed rolling resistance measurement procedure. However, the rolling resistance coefficients reported were from direct spindle force measurements divided by the compressive load on the tire. The radial tire descriptives, "good", "average", and "poor" were used solely for the purpose of identifying the relative rolling resistance ranking and thus did not imply an overall assessment of tire quality.

Data were collected using two technicians per vehicle; one person controlled the accelerator and brake as necessary to follow the particular EPA test cycle while the second person steered the vehicle and recorded fuel flow and actual distance data. Although the design of this experiment tended to account for vehicle and operator differences, considerable effort was spent to minimize differences between test vehicles. For example, vehicle mass and tire pressure were closely controlled and each driver/operator team continued to run tests with their particular test vehicle throughout the test program.

The test squence was the same for each parameter. The first day was spent in any vehicle preparation necessary, installation of instrumentation or components and a preliminary "dry run" test to insure all personnel were adequately instructed in the experimental needs. After any problems were resolved the vehicles were initially checked, then operated over the following cycles:

First 505 sec. of LA4 (Bag 1)

Next 867 sec. of LA4 (Bag 2)

505 sec. of LA4 (Bag 3)

Next 867 sec. of LA4 (Repeat of Bag 2)

EPA Highway Fuel Economy Cycle

At the end of this sequence a short break was taken by the vehicle operators while the parameter under investigation was changed. For example, tire pressures would be adjusted so that the vehicle which initially had the lower cold inflation pressure would now have the higher cold inflation pressure plus the temperature related pressure build-up which was observed from the tires which initially had the higher cold inflation pressure. The vehicles then returned to the track and the previous sequence was repeated.

After the close of each test day or at the beginning of the subsequent day all vehicle and ambient conditions data related to the immediately previous tests were telephoned to the EPA project officer if an EPA representative had not been at the track site during the testing. These data were immediately processed and plotted; therefore, never more than one test day elapsed between data collection and review. This rapid data review enabled detection of any equipment or other problems with minimal delay and also allowed the decision to continue with a given parameter, or to proceed to a subsequent investigation, to be made daily on the basis of the collected, analyzed data.

V. Data Analysis

The data obtained from this test program are presented in the Appendix A. Table A-1 presents the fuel consumption data for the comparison of an "Average" Radial Tire versus an "Average" Bias-Ply Tire for the tests conducted over the LA-4 driving cycle. Table A-2 presents the similar data obtained from the highway driving cycle. Tables A-3 and A-4 contain similar data from the "good" vs "poor" radial tire comparison, while Tables A-5 and A-6 present the pressure effects comparison.

These data can be analyzed by comparing the differences between the fuel consumption of the vehicles in each test configuration. For example, the difference, Delta 1, between vehicle 1 equipped with "average" radial tires and vehicle 2 equipped with bias-ply tires, is compared with the difference, Delta 2, between vehicle 1 equipped with bias-ply tires and vehicle 2 equipped with "average" radial tires. The values for the deltas are presented in each of the tables of the appendix, A-1 through A-6.

Two results may be obtained from the analysis of the paired differences. First, the average observed fuel consumption effect of the parameter under investigation may be obtained, and second, confidence intervals may also be obtained for these results.

A. Observed Effects of the Parameter Under Investigation

The mean observed effect of the parameter is simply one-half of the difference of the observed deltas. This relationship may be derived by considering the following equations. Let

B_1 = Base fuel consumption of vehicle 1

B_2 = Base fuel consumption of vehicle 2

E_1 = Fuel consumption effect of the parameter under investigation on vehicle 1

E_2 = Fuel consumption effect of the parameter under investigation on vehicle 2

For example, when vehicle 1 is equipped with radial tires and vehicle 2 is equipped with bias-ply tires the fuel consumption of the vehicles may be expressed as:

$$FC_1 = B_1 - E_1 \quad (1)$$

$$FC_2 = B_2$$

where

FC_1 = Fuel consumption of vehicle 1

FC_2 = Fuel consumption of vehicle 2

The difference in the fuel consumption of the vehicles is:

$$\text{Delta } 1 = FC_2 - FC_1 \quad (2)$$

$$= B_2 - (B_1 - E_1)$$

$$= (B_2 - B_1) + E_1$$

Likewise, when vehicle 2 is equipped with radials

$$FC_1 = B_1 \qquad (3)$$

$$FC_2 = B_2 - E_2$$

and

$$\text{Delta 2} = FC_2 - FC_1$$

$$= B_2 - E_2 - B_1 \qquad (4)$$

$$= (B_2 - B_1) - E_2$$

The average effect of the parameter on the two vehicles is given by:

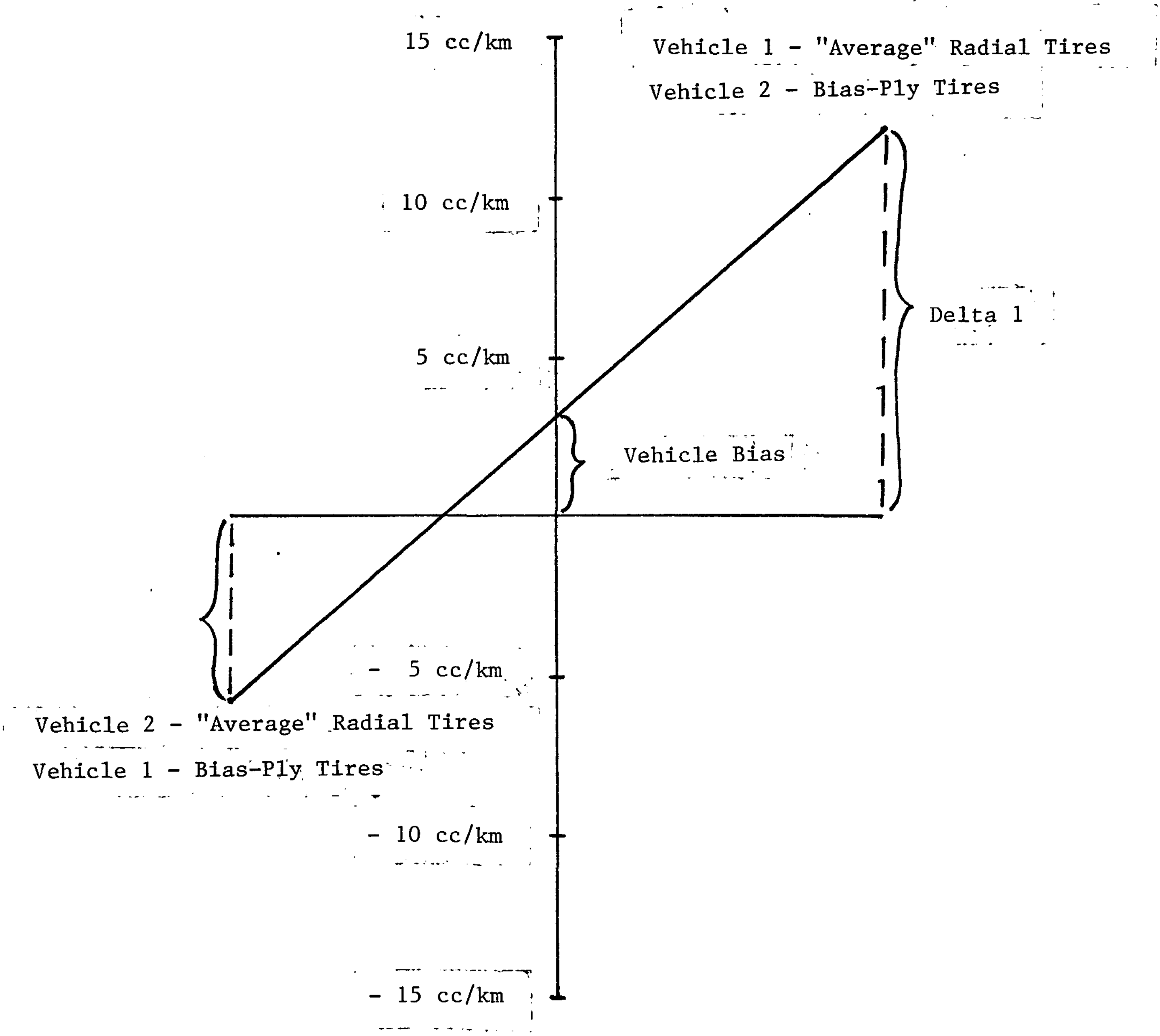
$$(\text{Delta 1} - \text{Delta 2})/2 = [[(B_2 - B_1) + E_1] - [(B_2 - B_1) - E_2]]/2$$

$$= [(B_2 - B_1) - (B_2 - B_1) + E_1 + E_2]/2$$

$$= (E_1 + E_2)/2 \qquad (5)$$

A graphical representation of this analysis is presented in Figure 1. The actual fuel consumption effect due to tire construction is

Figure 1


15 cc/km
Vehicle 1 - "Average" Radial Tires
Vehicle 2 - Bias-Ply Tires
10 cc/km
Delta 1
5 cc/km
Vehicle Bias
- 5 cc/km
Vehicle 2 - "Average" Radial Tires
Vehicle 1 - Bias-Ply Tires
- 10 cc/km
- 15 cc/km

equal to one-half the difference between Delta 1 and Delta 2, 0.5 [12.5-(-5.9)]. The positive intercept of the line connecting Delta 1 and Delta 2 indicates that vehicle 1 has three cc/km lower base fuel consumption than vehicle 2. This intercept would be zero if both vehicles have identical base fuel consumption.

The effect of each parameter, calculated in the above manner, is presented in Tables A-1 through A-6 of the Appendix. In addition, these results are summarized in Table 2, which is presented in the results section of this report.

B. Confidence Intervals

Equation (5) of the data analysis section shows that the desired results are expressed as the difference between two sample means. Consequently, the standard "t" test can be used to calculate confidence intervals about the observed differences. Specifically, a "t" test for the hypothesis of the difference between the observed means:

$$(\bar{x}_1 - \bar{x}_2) = \delta$$

is investigated to determine the magnitude of δ for which the null hypothesis may be rejected with 90 percent confidence. For example, the comparison of the fuel consumption differences with "Average" Radial vs. Bias-Ply Tires over the LA-4 cycle, may be investigated. In this case:

$\bar{x}_1$ = Delta 1 = 12.5 cc/km

s_1 = S.D. = 1.8 cc/km

n_1 = 8

$\bar{x}_2$ = Delta 2 = -5.9 cc/km

s_2 = S.D. = 1.2 cc/km

n_2 = 8

The "t" statistic value for tests with pooled variances is

$$t = \frac{[(\bar{x}_1 - \bar{x}_2) - \delta]}{\sqrt{(n_1-1)s_1^2+(n_2-1)s_2^2}} \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{(n_1 + n_2)}}$$

In this case the "null" hypothesis; that $x_1 - x_2 = \delta$, can be rejected with 90 percent confidence for all values of δ less than 17.1 cc/km or greater than 22.4 cc/km. Alternatively, we may state with 90 percent confidence that the true value of Delta 1 - Delta 2 lies between 17.1 cc/km and 22.4 cc/km.

Delta 1 - Delta 2 is shown by equation (5) to be simply twice the tire effect which is being investigated. Consequently, we may state that in this experiment the observed effect of radial tires was to reduce vehicle fuel consumption by 9.2 cc/km and that there was sufficient experimental precision to state that there is 90 percent confidence that the true reduction in fuel consumption of the vehicles was between 8.6 and 9.8 cc/km.

In more common engineering terminology it may be stated that the observed effect was 9.2 cc/km and the 90 percent confidence interval for the observation was approximately ±0.6 cc/km.

The observed values, and the approximate 90 percent confidence interval associated with each effect are shown in Table 2. These results are only slightly less precise than the experimental goal of obtaining results with a precision of ±0.5 cc/km at the 90 percent confidence level.

It is also informative to examine the null hypothesis $\bar{x}_1 - \bar{x}_2 = 0$.

When this hypothesis is examined it can be stated that there is a 99.9 percent certainty that the fuel consumption of radial and bias-ply tires are different, with the radial tires showing about 9.2 cc/km lower fuel consumption. Similarly, the radial vs. radial comparison, and the tire pressure comparison results are statistically significant at the 99.9 percent confidence level.

It is often convenient to discuss investigated effects in terms of percent changes in fuel consumption. Therefore, the percentage effects, computed by dividing the observed effect of the investigated parameter by the mean fuel consumed in all tests during the parameter investigation are presented. The 90 percent confidence limits, also expressed as a percentage of the mean fuel consumption, are also presented in Table 2.

VI. Results

The results of the data analysis are presented in Table 2. As expected, the effect of a transition from bias-ply to radial tires had the greatest effect, almost 6 percent. This result is very similar to the results of previous investigations.4/

The comparison of "good" versus "poor" radial tires resulted in a fuel consumption effect of about 3.5 percent while changing the tire inflation pressure by 8 psi resulted in fuel consumption change of approximately 3 percent. The observed pressure effect, 0.4 percent/psig, is similar to the effect which had been theoretically predicted.5/

A notable aspect of the results is that the effect of tire related parameters is very similar for either the LA-4 or the HFET driving cycles. Modeling of the energy demand of the vehicle over the test cycle indicates that tire contribution is approximately the same percentage of the total energy demand for each cycle. Consequently, the experimental results would be theoretically expected unless anomolous tire behavior occurred under transient conditions.

The effect on vehicle fuel consumption of the radial versus bias-ply tire comparison and the "good" versus "poor" radial tire comparison can be investigated as a function of the tire rolling resistances. These data are graphically presented in Figures 2 and 3. The slopes of the fuel consumption versus rolling resistance lines are presented in Table 3. Also presented in Table 3 are the slopes of the lines presented in terms of the percentage fuel consumption effect divided by the percentage change in the rolling resistance coefficient.

Table 2

Summary of Data Comparing Tire Constructions,
Variations Between Radial Tires, and Tire Pressures

	"Average" Radial vs. Bias-Ply		"Good" Radial vs. "Poor" Radial		28 psig vs. 20 psig	
	LA-4	HFET	LA-4	HFET	LA-4	HFET
Observed Effect (cc/km)	9.2	6.0	5.5	4.0	3.6	3.7
Limits of the 90 Percent Confidence Interval on the Observed Effect (cc/km)	±0.6	±1.0	±0.7	±1.2	±1.1	±1.3
Average Fuel Consumption During Comparative Tests (cc/km)	158.4	112.0	155.6	110.3	153.7	109.8
Percentage Effect (%)	5.8	5.4	3.5	3.6	2.3	3.4
Limits of the 90 Percent Confidence Interval on the Percentage Effect (%)	± 0.4	± 0.9	± 0.5	± 1.2	± 0.7	± 1.2

Table 3

Summary of Rolling Resistance Data Comparing
Tire Constructions, and Variations Between Radial Tires

	Slope of Observed Relationship		Sensitivity Coefficient	
	Δcc/km / ΔRRC		% change in FC / % change in RRC	
	LA-4	HFET	LA-4	HFET
"Average" Radial vs. Bias-ply				
Vehicle 1	1.675×10^3	2.525×10^3	0.184	0.200
Vehicle 2	1.275×10^3	2.100×10^3	0.142	0.163
"Good" Radial vs. "Poor" Radial				
Vehicle 1	1.696×10^3	1.826×10^3	0.171	0.132
Vehicle 2	2.130×10^3	2.913×10^3	0.214	0.205
Mean Values for each cycle	1.694×10^3	2.341×10^3	0.178	0.175
Grand Mean Values (both cycles)	2.018×10^3		0.176	

Figure 2
Fuel Consumption as a Function of Rolling Resistance
"Average" Radial vs. Bias-Ply

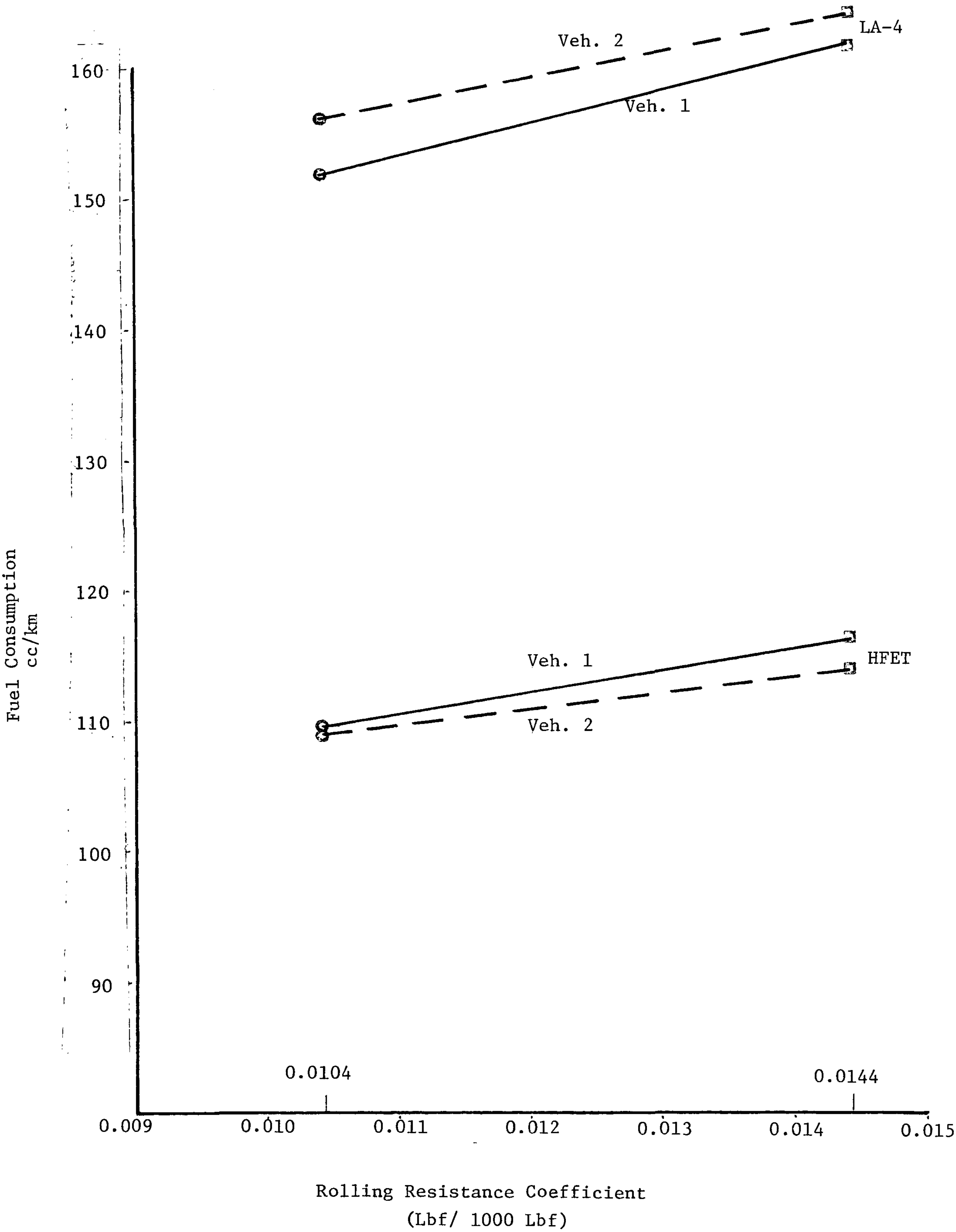
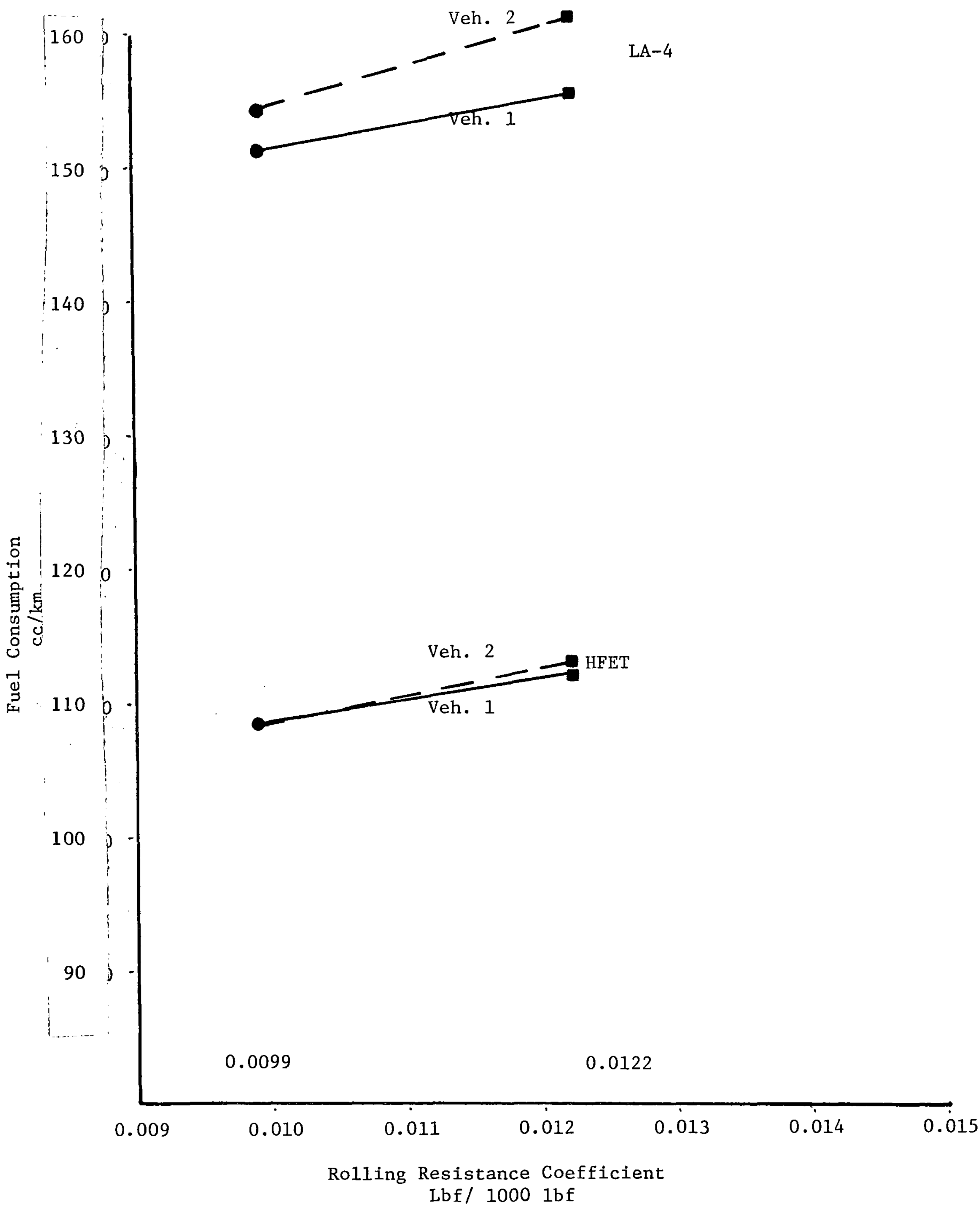


Figure 3
Fuel Consumption as a Function of Rolling Resistance
"Good" Radial vs. "Poor" Radial



Presented in this manner, the slope of the line may be considered as a fuel consumption/tire rolling resistance sensitivity coefficient. The data indicate that fuel consumption effects related by Δcc/km divided by ΔRRC (the slope) is more pronounced for the highway cycle test results than the LA-4 results. The sensitivity coefficients are calculated using the average values for vehicle 1 and vehicle 2 fuel consumption and the average RRC coefficients for the particular paired comparison. The calculated sensitivity coefficients are approximately equal for all comparison results. Consequently, the mean value, 0.176, can be interpreted as a 1.8 percent change in fuel consumption for each 10 percent change in the tire rolling resistance coefficient. This may be used as a good "rule of thumb" for predicting the vehicle fuel consumption effects of changes in tire rolling resistance.

VII. Conclusions

The results of this test program yielded the following conclusions.

(1) A typical radial tire is 5 to 6 percent more fuel efficient than a typical bias-ply tire. This result was achieved with high experimental precision over transient driving cycles and diverse ambient conditions. In practice, data were collected over a temperature range of 40-80°F with winds of 0-15 mph. Consequently, this result should be very representative of the effects of these tires in typical consumer service.

(2) Significant variations can exist between the fuel efficiency of radial tires from two different manufacturers. In this program an

effect of 3.5 percent was observed under conditions typical of consumer vehicle use.

(3) A substantial reduction in fuel consumption will occur with increased tire inflation pressure. In this study, representative of typical vehicle use and typical inflation pressures, a vehicle fuel consumption reduction of 0.4 percent was observed for each 1 psig increase in tire inflation pressure.

(4) The rolling resistance coefficient of a tire is a good predictor of the vehicle fuel consumption effects of the tires. Consequently, the tire rolling resistance coefficient is a good measure of the relative fuel efficiency of tires. As a general estimate, a 10 percent change in tire rolling resistance will result in a 1.8 percent change in the fuel consumption of the vehicle.

References

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5/ G. D. Thompson, Op Cit (3)

Appendix A

Table A-1

Fuel Consumption and Paired Fuel Consumption Differences for Comparison 1 ("Average" Radial vs Bias-Ply Tires) Using LA-4 Cycles.

	Vehicle 1: "Average" Radial Tires	Vehicle 2: Bias-Ply Tires	Difference Delta 1
	(cc/km)	(cc/km)	(cc/km)
	149.3	160.4	+ 11.1
	148.8	163.2	+ 14.4
	154.7	166.7	+ 12.0
	147.6	157.9	+ 10.3
	151.2	162.9	+ 11.7
	158.1	171.3	+ 13.2
	151.9	163.4	+ 11.5
	151.6	167.3	+ 15.7
Mean	151.7	164.3	+ 12.5
S.D.	3.4	4.2	1.8

	Vehicle 1: Bias-Ply Tires	Vehicle 2: "Average" Radial Tires	Difference Delta 2
	(cc/km)	(cc/km)	(cc/km)
	159.1	154.5	- 4.6
	159.9	154.8	- 5.1
	157.2	150.0	- 7.2
	161.1	155.3	- 5.8
	163.9	156.6	- 7.3
	167.3	160.3	- 7.0
	161.7	155.6	- 6.1
	164.2	160.2	- 4.0
Mean	161.8	155.9	- 5.9
S.D.	3.2	3.3	1.2

$$\text{Observed Effect} = \frac{12.5 - (-5.9)}{2} = 9.2 \text{ cc/km}$$

Average Fuel Consumption For All LA-4 Tests = 158.4 cc/km

Table A-2

"Average" Radial vs. Bias-Ply Comparison using Highway Cycles

	Vehicle 1: "Average" Radial Tires	Vehicle 2: Bias-Ply Tires	Difference Bias-Ply
	(cc/km)	(cc/km)	(cc/km)
	109.2	114.8	+ 5.6
	111.7	115.4	+ 3.7
	107.7	111.8	+ 4.1
	108.4	113.6	+ 5.2
Mean	109.3	113.9	+ 4.7
S.D.	1.7	1.6	0.9

	Vehicle 1: Bias-Ply Tires	Vehicle 2: "Average" Radial Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	116.0	107.9	- 8.1
	118.0	109.3	- 8.7
	115.6	110.1	- 5.5
	114.4	107.9	- 6.5
Mean	116.0	108.8	- 7.2
S.D.	1.5	1.1	1.5

$$\text{Observed Effect} = \frac{4.7 - (-7.2)}{2} = 6.0 \text{ cc/km}$$

Average Fuel Consumption For All HFET Tests = 112.0 cc/km

Table A-3

Fuel Consumption and Paired Fuel Consumption Differences for Comparison 2 ("Good" Radial vs. "Poor" Radial). using LA-4 Cycles.

	Vehicle 1: "Good" Radial Tires.	Vehicle 2: "Poor" Radial Tires.	Difference
	(cc/km)	(cc/km)	(cc/km)
	150.1	159.8	+ 9.7
	146.3	157.2	+ 10.9
	158.0	168.4	+ 10.4
	156.3	168.8	+ 12.5
	153.2	163.5	+ 10.3
	154.0	164.0	+ 10.0
	152.8	161.2	+ 8.4
	147.5	156.7	+ 9.3
	147.4	154.3	+ 6.9
	151.7	160.9	+ 9.2
	153.1	161.2	+ 8.1
	151.1	159.2	+ 8.1
	148.2	158.0	+ 9.8
	150.9	162.3	+ 11.4
Mean	151.5	161.1	+ 9.6
S.D.	3.4	4.2	1.5

Vehicle 1: "Poor" Radial Tires.	Vehicle 2: "Good" Radial Tires.	Difference
(cc/km)	(cc/km)	(cc/km)
160.5	158.2	- 2.3
163.2	155.9	- 7.3
154.5	154.0	- 0.5
155.6	155.3	- 0.3
160.4	157.1	- 3.3
153.6	154.6	+ 1.0
155.4	157.2	+ 1.8
153.9	154.3	+ 0.4
154.9	152.2	- 2.7
154.5	150.3	- 4.2

A-3 (cont'd)

	153.6	153.6	0.0
	152.1	154.6	+ 2.5
	150.8	152.1	+ 1.3
	155.7	151.9	- 3.8
	157.1	155.7	- 1.4
	155.7	152.9	- 2.8
Mean	155.7	154.4	- 1.4
S.D.	3.2	2.2	2.6

$$\text{Observed Effect} = \frac{9.6 - (-1.4)}{2} = 5.5 \text{ cc/km}$$

Average Fuel Consumption For All LA-4 Tests = 155.6 cc/km

Table A-4

Fuel Consumption and Paired Differences for Comparison 2 ("Good" Radial vs. "Poor" Radial) using Highway Cycles

	Vehicle 1: "Good" Radial Tires	Vehicle 2: "Poor" Radial Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	107.8	114.2	+ 6.4
	108.5	116.1	+ 7.6
	109.8	114.7	+ 4.9
	107.5	108.9	+ 1.4
	105.7	110.0	+ 4.3
	109.6	114.1	+ 4.5
Mean	108.2	113.0	+ 4.2
S.D.	1.5	2.9	2.7

	Vehicle 1: "Poor" Radial Tires	Vehicle 2: "Good" Radial Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	112.7	106.2	- 6.5
	109.9	105.7	- 4.2
	110.7	108.6	- 2.1
	110.9	107.7	- 3.2
	109.7	109.8	+ 0.1
	113.7	108.1	- 5.6
	114.1	108.5	- 5.6
	114.8	110.4	- 4.4
Mean	112.1	108.1	- 3.9
S.D.	2.0	1.6	2.2

$$\text{Observed Effect} = \frac{4.2 - (-3.9)}{2} = 4.0 \text{ cc/km}$$

Average Fuel Consumption For All HFET Tests = 110.3 cc/km

Table A-5

Fuel Consumption and Paired Differences for Comparison 3
(28 PSIG vs. 20 PSIG) using LA-4 Cycles

	Vehicle 1: 28 PSIG OEM Tires	Vehicle 2: 20 PSIG OEM Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	149.9	152.9	+ 3.0
	155.8	160.4	+ 4.6
	152.2	155.6	+ 3.4
	152.8	156.4	+ 3.6
	150.1	153.8	+ 3.7
Mean	152.2	155.8	+ 3.7
S.D.	2.4	2.9	0.6

	Vehicle 1: 20 PSIG OEM Tires	Vehicle 2: 28 PSIG OEM Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	155.2	154.2	- 1.0
	150.4	145.3	- 5.1
	157.0	153.5	- 3.5
	151.1	148.6	- 2.5
	162.3	155.1	- 7.5
	154.6	153.0	- 1.6
Mean	155.1	151.6	- 3.5
S.D.	4.3	3.8	2.3

Observed Effect $= \frac{3.7 - (-3.5)}{2} = 4.7$ cc/km

Average Fuel Consumption For All LA-4 Tests = 153.7 cc/km

Table A-6

Fuel Consumption and Paired Differences for Comparison 3
(28 PSIG vs. 20 PSIG) using Highway Cycles

	Vehicle 1: 28 PSIG OEM Tires	Vehicle 2: 20 PSIG OEM Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	110.0	115.5	+ 5.5
	110.7	112.6	+ 1.9
	105.2	109.6	+ 4.4
	110.6	110.9	+ 0.3
Mean	109.1	112.2	+ 3.0
S.D.	2.6	2.6	2.3

	Vehicle 1: 20 PSIG OEM Tires	Vehicle 2: 28 PSIG OEM Tires	Difference
	(cc/km)	(cc/km)	(cc/km)
	107.9	104.1	- 3.8
	112.9	108.5	- 4.4
	110.3	106.0	- 3.7
	113.7	108.5	- 5.2
Mean	111.2	106.8	- 4.3
S.D.	2.6	2.1	0.7

$$\text{Observed Effect} = \frac{3.0 - (-4.3)}{2} = 3.7 \text{ cc/km}$$

Average Fuel Consumption For All HFET Tests = 109.8 cc/km