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Determinants of Multiple Measures of Acceleration

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ABSTRACT

Statistical analyses of the acceleration capability of gasoline vehicles have focused on zero to 97 km/h acceleration rates and have concluded that peak power per kilogram is an appropriate single surrogate for acceleration capability. In this paper, statistical methods are used with data for 107 vehicles tested and reported by Consumers Union for 1986-1988 model years to estimate the determinants of contemporary gasoline vehicle acceleration capability under various conditions, adding new variables to the statistical tests reported by others. Like previous studies, this analysis determined that power and weight provide the most information about acceleration capability. Using a model formulation unlike other studies, this study found that engine displacement also provides statistically significant improvements in explanation of 0-48, 0-97, and 48-97 km/h acceleration times. The coefficients of the equations imply that the use of smaller displacement engines, holding peak power constant, diminishes start-up and 0-97 km/h acceleration capability. A separate equation is estimated to illustrate the effects of advanced engine technologies on displacement, controlling for power. This equation is used in conjunction with the acceleration equations to illustrate a method of estimating performance-equivalent engine substitutions when engine technologies change. Transmission type was important for start-up acceleration, with automatic-transmission-equipped vehicles being significantly slower than stick-shift-equipped vehicles. Fuel injection was found to significantly improve start-up acceleration. Variables proxying aerodynamic-drag effects tended to be significant determinants of acceleration in the higher-speed equations, but not for start-up acceleration. Estimated aerodynamic drag effects indicated that drag slows down 0-97, 48-97, and 72-105 km/h acceleration of pickup trucks and sport utility vehicles more than passenger cars and vans. The goodness-of-fit (R^2) of the 0-48 km/h acceleration equations was far poorer than for the others.

INTRODUCTION

In the comparison of conventional and advanced vehicles, one issue which arises is the question of performance equivalence. For example, the ratio of instantaneous start-up acceleration rate capability to acceleration capability at steady highway speeds is far higher for electric vehicles than for

contemporary gasoline vehicles. As a part of a larger DOE research project designed to fairly compare the capabilities of gasoline and advanced vehicles, this study estimates the determinants of contemporary gasoline vehicle acceleration capability under various conditions, adding new variables to the statistical tests. To date, statistical analyses of the acceleration capability of gasoline vehicles have focused on zero to 97 km/h acceleration rates and have concluded that peak power per kilogram (kW/kg) is an appropriate single surrogate for acceleration capability (1,2). The U.S. Environmental Protection Agency (EPA) has been using such a relationship to estimate the change in performance capability of new cars and light trucks from 1974 onward (3). Table 7-6 of the recent National Academy of Sciences Report "Automotive Fuel Economy: How Far Should We Go?" (4) based its estimate of change in performance capability on the change in vehicle power per kilogram.

In attempting to judgmentally determine "performance equivalence", Ford engineers working with statisticians Berger, Smith, and Andrews (5) reportedly took into account start-up acceleration, 0-97 km/h time, and acceleration from a steady 105 km/h in developing estimates of performance equivalence for comparison of the fuel economy improvement possible for various technologies, holding performance constant. This effort was apparently based on engineering judgment, since no quantification method was described in the study. A common concern about reduction of engine displacement is the loss of the feel of power when starting from a stop. Yet efforts to quantify a measure of performance in most evaluations of vehicles rely on the available statistical results establishing a simple link between 0-97 km/h time and kilowatts per kilogram. In this paper we develop some statistical results which address the determinants of start-up acceleration, using 0-48 km/h acceleration as a proxy, passing acceleration within legal speed ranges (72-105 km/h), and also estimate the traditional 0-97 km/h time. In addition a 48-97 km/h time is examined.

METHOD

Consumers Union field tests and reports the acceleration of automobiles under three conditions, as well as provides enough technical detail on vehicles to conduct a statistical examination of the major determinants of acceleration under those test conditions. Other sources (such as *Car and Driver*)

compile this information but use inconsistent test methods and compile vehicle descriptors differently. Acceleration from 0-48, 0-97, and 72-105 km/h is reported by Consumers Union.

In this study, we use a data base which was convenient to assemble. In 1989 Consumers Union published a summary of its test results for the years 1986-1988 in a used car buying guide (6). A data base of 107 vehicles has been assembled from the Consumers Union test and vehicle specifications information. The sample is dominated by passenger cars. However, four pickup trucks, four 4wd sport-utility vehicles, and eight minivans are included.

VARIABLES

Consumers Union Input Variables Used in Presented Model

Z48 = reported time from 0 to 48 km/h, in seconds

Z97 = reported time from 0 to 97 km/h, in seconds

P72105 = reported time from 72 to 105 km/h, in seconds

HP = net peak power

L = displacement in liters

CW = curb weight

Wd = width

Ht = height from door top to ground

T = transmission type (= 0 if stick and 1 if automatic)

Derived Input Variables Used in Presented Model

P4897 = passing time from 48 to 97 km/h, by subtracting Z48 from Z97

ln(Area) = ln of Area (the quantity Wd times Ht); used as a surrogate for frontal area — coefficient of drag [C_d] not available)

Car = 1 for passenger cars, 0 for all other vehicles (91 passenger cars)

CArea = Car times ln(Area)

Van = 1 for passenger minivans, 0 for all other vehicles (8 passenger minivans)

VArea = Van times ln(Area)

FI = Fuel injected (either multipoint or throttle body) engines = 1, others = 0

TS1 = Engine technology set 1 - carbureted or fuel-injected pushrod, two-valve per cylinder engines = 1, others = 0 (32 vehicle types, 28 of which fuel injected)

TS2 = Engine technology set 2 - carbureted, overhead-camshaft, two-valve per cylinder engines not turbocharged = 1, others = 0 (24 vehicle types)

TS3 = Engine technology set 3 - fuel-injected, overhead-camshaft, two-valve per cylinder engines not turbocharged = 1, others = 0 (32 vehicle types)

TS4 = Engine technology set 4 - carbureted, overhead-camshaft, three-valve per cylinder engine not turbocharged = 1, others = 0 (1 vehicle type)

TS5 = Engine technology set 5 - carbureted, overhead-camshaft, four-valve per cylinder engine not turbocharged = 1, others = 0 (1 vehicle type)

TS6 = Engine technology set 6 - fuel-injected, overhead-camshaft, three-valve per cylinder engines not turbocharged = 1, others = 0 (2 vehicle types)

TS7 = Engine technology set 7 - fuel-injected, overhead-camshaft, four-valve per cylinder engines not turbocharged = 1, others = 0 (9 vehicle types)

TS8 = Engine technology set 8 - fuel-injected, overhead-camshaft, two-valve per cylinder turbocharged engines = 1, others = 0 (5 vehicle types)

TS9 = Engine technology set 7 - fuel-injected, overhead-camshaft, four-valve per cylinder turbocharged engines = 1, others = 0 (1 vehicle type)

The CArea and VArea variables will be recognized as multiplicative dummy variables (7) which can be used to test for a different drag-induced reduction of acceleration for the frontal area of cars and vans in comparison with that of the eight pickup trucks and sport utility vehicles. Such a difference should exist if the C_d for these vehicles is significantly less than for the pickup trucks and sport utility vehicles. The configuration of the dummy variables was the best arrangement of tests to show that there is evidence that drag not only affects fuel economy, but also affects acceleration capability at higher speeds. Note that preliminary equations used this technique to separately test for differences of C_d for vans, pickup trucks and sport utility vehicles. These experiments indicated that the effect of frontal area for the pickup trucks and sport utility vehicles could not be distinguished from one another, so they were grouped together. Vans and cars were not statistically significantly different from one another, but comparison of the van and car area coefficients indicated that the van coefficients consistently had a larger negative magnitude than the car coefficients, with the differences nearly significant in some cases.

The form of the statistical models tested is a logarithmic, or multiplicative model such as that developed by Berger, Smith and Andrews (5). In this form of model, each of the included variables is logged, and an additive model is estimated. The resulting coefficients of independent variables are interpreted as the elasticity of response of the dependent variable to the tested independent variable. The presented model is

$$\ln(\text{ACC}) = a_0 + a_1 \cdot \ln(\text{HP}) + a_2 \cdot \ln(\text{CW}) + a_3 \cdot \ln(\text{L}) + a_4 \cdot \text{T} + a_5 \cdot \ln(\text{Area}) + a_6 \cdot \text{CArea} + a_7 \cdot \text{VArea} + a_8 \cdot \text{FI} + \text{error}, \quad (1)$$

where ACC = Z48, Z97, P4897, or P72105. As indicated in EQ (1), the ACC, HP, CW, L, and Area variables are included in natural log form, while T and FI remain 0 or 1 dummy variables. When the two area dummy variables are nonzero, they are also the natural log of Area. The same equation is estimated for each of the four acceleration tests. The a_1 to a_3 and a_5 coefficients are interpretable as elasticities (the percent change in elapsed time per one percent change in the tested independent variable). The a_4 coefficient is interpretable as a test whether the intercept term a_0 is significantly different for automatic-transmission-equipped vehicles than for stick-transmission-equipped vehicles. The a_6 and a_7 coefficients are interpretable as estimates of whether the C_d (and therefore net elasticity) for the separate class of vehicles is significantly different from that for pickup trucks and sport utility vehicles. For example, to obtain the net elasticity estimate for the effective drag area of minivans, one adds a_5 and a_7 . Then,

$$\text{ACC} = e^{a_0} \cdot \text{HP}^{a_1} \cdot \text{CW}^{a_2} \cdot \text{L}^{a_3} \cdot (\text{Area})^{(a_5 + a_6 \cdot \text{Car} + a_7 \cdot \text{Van})} \cdot e^{a_4 \cdot \text{T}} \cdot e^{a_8 \cdot \text{FI}} \quad (2)$$

where e = the natural log.

Although the logarithmic model is preferred for its convenience in directly estimating elasticities, it also happens to be superior statistically to a linear model. The goodness of fit (R^2) of analogous linear models were consistently lower than those for ln-ln models tested, and the properties of the residuals were far more well-behaved. The ln-ln model consistently eliminated "U"-shaped residual patterns present in the linear models.

A difference of the form of model tested here and those tested by Young (2) and by Malliaris, Hsia, and Gould (MHG) (1) is that it does not place restrictions on the relationship of coefficients of the key tested variables. Young and MHG presented results for a simple model of the form

$$\text{ACC} = e^{a_0} \cdot (\text{HP}/\text{CW})^b \quad (3)$$

This is equivalent to testing a restricted simplified model of the general form [(EQ (2))], as follows:

$$\text{ACC} = e^{a_0} \cdot \text{HP}^{a_1} \cdot \text{CW}^{a_2} \cdot \text{L}^{a_3}, \quad (4)$$

with the restrictions that $a_2 = -a_1 = b$ and that $a_3 = 0$.

Young also tested a model of the form

$$\text{ACC} = e^{a_0} \cdot (\text{L}/\text{CW})^c \quad (5)$$

with very poor results ($R^2 = 0.20$). This model was equivalent to placing the alternative restrictions on EQ (4) that $a_3 = -a_2 = c$ and that $a_1 = 0$.

The formulation presented here does not restrict the coefficients (exponents) of the key variables of interest, since it is a more general form. If the forms tested by Young and by

MHG were the true relationships, this general equation would be able to statistically recover them from the data.

The results for all 107 vehicles and all four acceleration tests are presented in Table 1. The entries of Table 1 are estimated coefficients and t-statistics

FINDINGS

GOODNESS OF FIT - The R^2 values for the three models show that 0 to 48 km/h acceleration is poorly explained ($R^2 = 0.50$). Results for 0 to 97 km/h ($R^2 = 0.84$) are similar to those obtained by Young (2) for cars and trucks ($R^2 = 0.87$) and by MHG (1) ($R^2 = 0.85$). Results for the P4897 and P72105 are about as good as for Z97. Note that statistical estimates of regression equations of the form presented by Young and by MHG [EQ (3)] result in nearly as much explanatory power as the model here. R^2 results for Z97 are 0.80, for P4897 are 0.81, and for P72105 are 0.76, each within 0.04 of the value for the more complex equation. However, in the case of the Z48 equation, this simpler form equation does not have nearly as much explanatory power relative to the complex model. The R^2 drops to 0.35, well below the 0.50 value obtained with the complex model tested here.

INTERCEPT TERM - The intercept term is consistently insignificant.

PEAK POWER AND WEIGHT - A property of most of the power and weight elasticity estimates is that they are approximately equal in magnitude, but opposite in sign. As in prior analyses, these two variables provide most of the explanatory power. When rounded to a single significant digit, the 0 to 97 km/h elapsed time elasticities of power (-0.8) and weight (0.8) are slightly smaller in absolute value than the -0.9 value obtained by Young for power per kilogram for 183 cars and 50 trucks and about the same as the value obtained by MHG (-0.8). Since the measure available is peak power, it is probably not surprising that a 1% increase in peak power is estimated to cause a greater reduction in 0 to 97 km/h acceleration time than in start-up acceleration time, and in passing acceleration times than in 0 to 97 km/h acceleration time. The importance of weight and power is estimated to peak in the determination of 48-97 km/h passing time, with both elasticities rising to absolute values of 1.0. Changes in weight and/or peak power are estimated to have about half of the effect on start-up acceleration time (0-48 km/h) as on the other acceleration test times. Further, in the case of the 0-48 km/h equation, the restriction that $a_2 = -a_1 = b$ is clearly invalid, and a regression of the form of EQ (3) should be rejected. In this case, the absolute value of $a_1 = 0.28$, while that of $a_2 = 0.53$, significantly different numbers.

DISPLACEMENT - Young tested equations which included engine displacement, but only instead of power rather than in addition to power. In these tests, we have estimated the effect of engine displacement, after the effects of power and weight are taken into account, by estimating a general form of equation, as discussed above. When measured in this fashion, engine displacement is estimated to be important, namely in the start-up acceleration test. The absolute value of the consistently negative engine displacement elasticity estimates declined steadily as the speed range of the test increased, dropping steadily from 0.28 in the Z48 test to 0.08 in the

P72105 test. The adjusted R^2 of the Z48 equation, with engine displacement removed, dropped to 0.38 (not shown), a decline of 17% from the R^2 value in Table 1. However, when the same test was applied to the Z97 equation, the decline in R^2 value was only 2% and was 0.5% or less in the passing equations. Accordingly, the prior omissions of engine displacement from equations determining 0 to 97 km/h time is not surprising and is not a large source of error. For acceleration at low speeds, however, inclusion of engine displacement is important. The Z48 weight elasticity estimate drops sharply when engine displacement is added to the equation (not shown). Thus, as far as competition with the EV in urban driving conditions is concerned, the inclusion of engine displacement in the Z48 equation implies smaller urban driving performance benefit to gasoline vehicles through the use of weight-reducing measures.

We assume that engine displacement is a proxy for start-up and low revolutions-per-minute torque and power. Note that we tried equations with peak torque added to the equations with key variables, and peak torque did not enter significantly. Accordingly, it was dropped from our analysis.

TRANSMISSION TYPE - The coefficients of the automatic transmission dummy variable imply a time lag in engagement of the automatic transmission after the accelerator is depressed when starting from a stop. Note that Consumer Reports tests do not use the brake to hold the vehicle in place while depressing the accelerator, when testing start-up acceleration of automatic-transmission-equipped vehicles. Given the results — a declining percent time reduction due to automatics from the Z48 through the passing tests — the problem of acceleration delay for automatics appears confined to start-up.

FRONTAL AREA - The absolute value of the various frontal area coefficients rises sharply from the Z48 to the Z97 test through the P4897 test and then drops slightly for the P72105 test. Note that the top speed of the P72105 test is only 8 km/h higher than the Z97 test and that the average duration of the P72105 test is 8.4 s, while the P4897 test duration is 8.6 s — only 0.2 s more for an additional 16 km/h gain. The two tests are started differently: the P72105 test starts with a steady 72 km/h, while the P4897 test is actually a segment of a 0-97 km/h test, where hard acceleration through 48 km/h is ongoing. Accordingly, the rate of acceleration is significantly greater for the P4897 test than for the P72105 test. This probably explains the fact that pickup truck and sport utility frontal-area drag-induced delay is estimated to be significant in the passing test with the lower-end speed, while it is not estimated to be significant in the test occurring over the highest speed range. Accordingly, the absolute value and estimated level of statistical significance of the frontal area variables is highest for the passing test with the highest rate of acceleration. The estimated coefficients imply that the coefficients of drag of passenger cars and vans are significantly less than those for pickup truck and sport utility vehicles. Though the differences are not statistically significant, the results imply that minivans have a lower drag coefficient than do passenger cars.

FUEL INJECTION - A number of equations were tested with engine technology sets as described in the variable section. The numerous individual tests indicated that the distinctions among different technologies did not provide any improvement in explanatory power, with the exception of fuel

injection vs. no fuel injection comparisons for the 0-48 km/h equation. Accordingly, we constructed the FI dummy variable and found that it did provide a statistically significant improvement in the explanatory power of the 0-48 km/h equation. Addition of the FI variable increased the R^2 from 0.46 to 0.50. The coefficient for the FI variable in the 0-48 km/h equation implies that addition of fuel injection will reduce 0-48 km/h time by 2%.

ENGINE TECHNOLOGIES - The finding that engine technologies did not seem to matter was a suspect result. We noted that it is a result obtained *after* displacement is in the equation. We also noted that the adoption of the advanced technologies allows generation of more peak power per liter. Reflection indicated that estimation of the relationship between displacement per unit of power and engine technology would allow us to substitute a reduction in displacement when assuming a new engine technology with greater peak power per liter. The equation estimated is of the form

$$\ln(L/HP) = h_0 + h_i \cdot TS_i + \text{error}, \quad (6)$$

where $i = 2$ to 9.

Expressed in the form of EQ (2), EQ (6) becomes

$$L/HP = e^{h_0} e^{h_i \cdot TS_i}, \quad (7)$$

and the coefficients become estimates of how large a percent reduction in displacement will result when a given amount of power is provided by engine technology set TS_i instead of engine technology set TS_1 , the latter being a pushrod two-valve engine. Estimation of EQ (6) gives the following results (t-values are given in parentheses)

$\ln(L/HP) = 3.18$ (160.1)*	$-0.11 TS_2$ (-3.72)*	$-0.19 TS_3$ (-6.87)*
$-0.17 TS_4$ (-1.50)	$-0.31 TS_5$ (-2.71)*	$-0.39 TS_6$ (-4.74)*
$-0.41 TS_7$ (-9.60)*	$-0.53 TS_8$ (-9.72)*	$-0.66 TS_9$ (-5.79)*

Adj. $R^2 = 0.64$

* Statistical significance at the 0.01 probability level

This equation indicates that seven of the eight engine technology sets, from number two through nine, will have a significantly smaller engine displacement than the base pushrod two-valve per cylinder technology of engine technology set 1, for a given peak power. The coefficients for technology sets TS_6 and TS_7 imply that a fuel-injected overhead-camshaft engine with three or four valves per cylinder will have about a 40% smaller displacement than a fuel-injected pushrod two-valve per cylinder engine with the same peak power. These engine size reduction coefficients can be used in combination with the coefficients of the acceleration equations to estimate the changes in engine size and peak power that would be necessary to maintain "performance equivalence" as a new, downsized engine of advanced technology is substituted for a larger, more conventional technology engine. For example, if we use TS_6 and TS_7 coefficient approximations of -0.40, then the 0-97 km/h performance

reduction percentage (i.e., percent increase in elapsed time) that would result from substituting an equivalent peak power TS6 or TS7 technology for a TS1 engine technology would be $-40\% \times -20\%$ (Z97 coefficient a_3), or 8%. To compensate for this loss, a larger TS6 or TS7 engine could be adopted. An approximate estimate of the compensating increase in size needed can be obtained by forcing the percent increase in size, p , to be determined by the equation, $0.08 = -0.75 \times p$ where -0.75 is the coefficient for the response of 0-97 km/h acceleration to change in peak power. In this case, the advanced technology engine would have to be approximately 11% larger ($p = -0.08/0.75 = 0.11$) in power than the base engine to give the same rate of acceleration. Note, however, that this is only an approximation, since the increase in size estimated tends to offset the effects of the initial round estimate of lost performance due to reduction in engine displacement. Now the engine would be estimated to be only 34% [$= 100 \cdot [1 - 1.11 \cdot (1 - 0.4)]$] smaller than the original engine. To get an "equilibrium" estimate by this method, one can go through several iterations until estimates tend to remain constant in repeated rounds. Note that this computation ignores engine weight change.

We can also set up equations to solve for the equilibrium constant weight relationship. The performance loss due to reduction in engine size for the advanced technology has to be offset by a performance gain achieved through a higher peak power. Thus, for a given performance equation, the following must be true to have equal performance:

$$a_3 \cdot \ln(L_n/L_b) = -a_1 \cdot \ln(HP_n/HP_b), \quad (8)$$

where

L_n = displacement of new engine,

L_b = displacement of base engine,

HP_n = power of the new engine, and

HP_b = power of the base engine.

From EQ (7), we can write:

$$L = HP \cdot (e^{h_0} e^{h_1 \cdot TS_i}). \quad (9)$$

If the base engine is technology set 1, the coefficient h_1 has been, by assumption, set equal to zero, so

$$L_b = HP_b \cdot (e^{h_0} e^{h_1}) = HP_b \cdot (e^{h_0} e^0) = HP_b \cdot (e^{h_0}),$$

and $L_n = HP_n \cdot (e^{h_0} e^{h_n})$, so

$$\begin{aligned} \ln(L_n/L_b) &= \ln([HP_n \cdot (e^{h_0} e^{h_n})]/[HP_b \cdot (e^{h_0})]) \\ &= \ln(HP_n \cdot e^{h_n}/HP_b) \\ &= \ln(e^{h_n} [HP_n/HP_b]) = h_n + \ln[HP_n/HP_b]. \end{aligned} \quad (10)$$

Substituting the solution for EQ (10) into EQ (8), one obtains:

$$a_3 \cdot (h_n + \ln[HP_n/HP_b]) = -a_1 \cdot \ln(HP_n/HP_b)$$

and

$$(a_3 + a_1)(\ln(HP_n/HP_b)) = -a_3 \cdot h_n.$$

$$\text{Then } \ln(HP_n/HP_b) = -(a_3 \cdot h_n)/(a_1 + a_3). \quad (11)$$

Substituting the right hand side of EQ (11) into EQ (8), one can solve for $\ln(L_n/L_b)$ to obtain

$$\ln(L_n/L_b) = (a_1 \cdot h_n)/(a_1 + a_3). \quad (12)$$

For the constant performance substitution of a fixed weight new engine technology, EQ (11) allows estimation of the increase in power necessary to offset the performance decline caused by displacement reduction per unit of peak power, as advanced engine technologies replace a base technology. EQ (12) allows estimation of the allowable decline in displacement, consistent with maintaining enough peak power to keep estimated acceleration time constant. The results of estimates using EQS (11) and (12) can be expressed as percentages. Table 2 illustrates the "performance equivalent" engine power and size changes that result from EQS (11) and (12) and the a_1 and a_3 coefficients from Table 1, combined with an assumed h_n value of -0.40 . This is the same as our sample case, approximately illustrating the switch from fuel-injected pushrod two-valve per cylinder technology to fuel-injected overhead-camshaft three-to-four valve per cylinder technology.

Table 2 illustrates that the estimates in this paper support the argument that a performance equivalent substitution of an advanced technology, overhead-camshaft multiple-valve engine for a conventional pushrod two-valve engine requires a higher level of peak power in the advanced engine if performance is to be held constant. It also supports the argument that, if U.S. consumers have a stronger preference for start-up acceleration than for 0 to 97 km/h or passing acceleration, the downsizing of advanced engines which would be acceptable to the consumer is significantly less than would be calculated by using 0 to 97 km/h comparisons. Since it also indicates that the relative performance effects of advanced engine downsizing are very much different for 0 to 48 km/h acceleration than for other measures of acceleration, those who measure "performance equivalence" should take start-up acceleration into account.

We note that the model of constant performance engine size and peak power change is not yet complete, because the effect of engine downsizing on vehicle weight has not been included. When included, this will reduce the peak power increases needed to hold performance constant. However, the offsetting effect of weight reduction will be least for the 0-48 km/h acceleration case, given the low value of a_2 in that case.

For those vehicles for which consumers place a high priority on acceleration in congested driving with low top speeds, this analysis suggests that advanced internal combustion engine engines are not as promising in this type of use as in higher-speed driving. Electric vehicles, which have good start-up acceleration, but poor high-speed acceleration, may, with the help of illustrations from this research, seem more promising in light of the apparent relative shortcomings of advanced engines in congested low top-speed driving.

SUMMARY

Like previous studies, this analysis determined that power and weight provide the most information about acceleration capability. Using a model formulation less restricted than used in other studies, this study found that engine displacement also provides statistically significant improvements in explanation of 0-48, 0-97, and 48-97 km/h acceleration times, with greatest improvement for the 0-48 km/h test. The coefficients of the equations imply that the use of smaller displacement engines, holding peak power and vehicle weight constant, diminishes start-up, 0-97, and 48-97 km/h acceleration capability. Transmission type was important for start-up acceleration, with automatic-transmission-equipped vehicles being significantly slower than stick-shift-equipped vehicles. Variables proxying aerodynamic drag effects tended to be significant determinants of high-speed acceleration capability, but not start-up acceleration. Estimated aerodynamic drag effects indicated that drag slows down 0-97, 48-97, and 72-105 km/h acceleration of pickup trucks and sport utility vehicles more than acceleration of passenger cars and vans. Fuel injection was found to contribute significantly to 0-48 km/h acceleration. The goodness-of-fit (R^2) of the 0-48 km/h acceleration equations was far poorer than for the other three. Performance equivalent downsizing of advanced-engine technologies was found to be a complex question which requires inclusion of start-up (0-48 km/h), 0-97 km/h, and passing acceleration measures to provide a comprehensive understanding of how performance will change for a given change in engine size and peak power. The estimates of constant performance change in engine power and size are illustrative, since vehicle weight reduction effects of smaller engines are not yet estimated.

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REFERENCES

1. Malliaris, A.C., H. Hsia, and H. Gould, 1976, *Concise Description of Auto Fuel Economy and Performance in Recent Model Years*, SAE Paper 760045, (Feb. 23-27).
2. Young, Y.R., 1991, *Regression Analysis for Performance of Light Duty Vehicles*, National Highway Traffic Safety Administration Report DOT HS 807 763, National Highway Traffic Safety Administration, Washington, DC.
3. Heavenrich, R.M., J.D. Murrell, and K.H. Hellman, 1991, *Light-Duty Automotive Technology and Fuel Economy Trends Through 1991*, EPA/AA/CTAB/91-02, U.S. Environmental Protection Agency, Ann Arbor, MI.
4. National Research Council, 1992, *Automotive Fuel Economy: How Far Should We Go?*, National Academy Press, Washington, DC.
5. Berger, J.O., M.H. Smith, and R.W. Andrews, 1990, "A System for Estimating Fuel Economy Potential due to Technology Improvements," presented at the workshop of the Committee on Fuel Economy of Automobiles and Light Trucks, Irvine, Calif., July 8-12. University of Michigan, Ann Arbor, MI.
6. Markovich, 1989, *Used Car Buying Guide 1989*, Consumers Union, Mount Vernon, New York, NY.
7. Cleary, J., and H. Levenbach, 1982, *The Professional Forecaster*, Lifetime Learning Publications, Belmont, CA.

Table 1. Results of Regression Model by Acceleration Test

	Estimated Coefficients and t-Statistics			
	ln(Z48)	ln(Z97)	ln(P4897)	ln(P72105)
Mean duration of test, s	4.6	13.2	8.6	8.4
Variable (coeff.)				
Intercept (a_0)	0.79 (0.86)	0.13 (0.20)	-1.22 (-1.58)	-0.08 (-0.10)
ln (HP) (a_1)	-0.28 (-3.65)***	-0.75 (-14.3)***	-1.02 (-15.8)***	-0.89 (-13.0)***
ln (Weight) (a_2)	0.53 (3.18)***	0.85 (7.39)***	1.0 (7.15)***	0.77 (5.16)***
ln (Displacement) (a_3)	-0.29 (-3.99)***	-0.20 (-3.94)***	-0.14 (-2.28)**	-0.08 (-1.28)
Automatic (a_4) (dummy variable)	0.10 (3.25)***	0.04 (1.85)*	0.01 (0.30)	0.02 (0.80)
ln(Frontal Area) (a_5) (estimates truck effect)	0.02 (0.07)	0.26 (1.44)	0.42 (1.88)*	0.32 (1.34)
Car • ln(Area) (a_6) (difference from trucks)	0.00 (0.04)	-0.02 (-1.85)*	-0.03 (-2.26)**	-0.03 (2.27)**
Van • ln(Area) (a_7) (difference from trucks)	-0.02 (-0.92)	-0.04 (-3.17)***	-0.05 (-3.47)***	-0.04 (-2.28)**
Fuel Injection (a_8) (dummy variable)	-0.02 (2.99)***	-0.03 (-1.37)	0.01 (0.81)	0.00 (0.04)
Adjusted R ²	0.50	0.84	0.84	0.80

*** Statistical significance at the 0.01 probability level.

** Statistical significance at the 0.05 probability level.

* Statistical significance at the 0.10 probability level.

Table 2. Example Constant Performance Percent Change in Engine Size and Power by Acceleration Model^a

	Constant Performance Change (%)			
	Z48	Z97	P4897	P72105
Peak Power	20	8.4	4.3	3.3
Displacement	-20	-32	-35	-37

^a Switch in which the advanced engine achieves peak power with 40% less displacement. However, estimates assume no change in vehicle weight due to engine downsizing.

END

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11 / 16 / 193