Title: Acceleration Performance Trends and the Evolving Relationship Between Power, Weight, and Acceleration in U.S. Light-Duty Vehicles: A Linear Regression Analysis.

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ABSTRACT

The acceleration performance of light-duty vehicles has implications for the energy usage of those vehicles, their attractiveness to consumers, and how they are driven. Despite this importance, many investigators rely on correlations from the 1970s for estimating performance. This paper presents a set of linear regression models for estimating acceleration times from 0-48, 0-97, and 72-105 km/h (0-30, 0-60, and 45-65 mph), based on engine power, vehicle weight, body style, and basic powertrain characteristics of more than 1000 vehicles tested by Consumer Reports magazine between 1975 and 2010. Importantly, the paper includes estimates of fixed effects for each year, capturing technological improvements not directly observed in the data set and making the models appropriate for estimating performance of vehicles from many different model years. Results indicate that contemporary vehicles are better able to transform engine power into acceleration performance than were vehicles in the past, yielding acceleration times 20-30% faster than comparable vehicles in the 1970s. Most of this improvement appears to have occurred before 1990, and the estimated effect is larger for 0-48 km/h acceleration than for higher-speed acceleration. One of the reported models was applied to historic sales and specification data for United States vehicles, and the results indicate that new vehicles in the U.S. today average 8.8 seconds from 0-97 km/h, 0.9 seconds (10%) faster than previously thought. Interestingly, the trends in 0-97 km/h acceleration times are consistent with exponential decay toward an asymptote, and today's vehicles are within one second of the estimated asymptotic acceleration time.

1. INTRODUCTION

Understanding vehicle acceleration performance is important to transportation analysts and researchers for several reasons. First, acceleration can be traded off against other vehicle attributes, including fuel economy. All else being equal, larger improvements in acceleration performance over time mean smaller improvements in fuel economy, leading to higher energy consumption. Second, the acceleration performance of a vehicle can affect its utility to consumers, influencing purchase decisions. Finally, the acceleration capabilities of vehicles may influence how aggressively they end up being driven, affecting in-use fuel consumption (*1*). The objective of this work was to develop an improved method for estimating vehicle acceleration performance based on other vehicle attributes, and to quantify the annual improvements in acceleration performance that are due to factors beyond basic ones like increased power-to-weight ratio.

The average acceleration performance of new vehicles sold in the United States has been improving steadily since the early 1980s, while fuel consumption has changed little. Figure 1 shows the average 0-97 km/h (0-60 mph) acceleration times and average fuel consumption for new cars and light trucks in the U.S. since 1975, as reported by the U.S. Environmental Protection Agency (*2*). Despite the substantial reductions in acceleration times that are evident in these oft-cited numbers, the results reported in this paper will show that the actual rate of change in acceleration times has been even faster, and that the estimates in Figure 1 overstate acceleration times for contemporary U.S. vehicles by an average of 0.9 seconds, or 10%.

Acceleration performance is commonly reported as the time needed to accelerate a vehicle between two speeds at wide-open throttle. Three common acceleration metrics are investigated in this paper:

- Z48: Time to accelerate from 0-48 km/h (0-30 mph)
- Z97: Time to accelerate from 0-97 km/h (0-60 mph)
- P72105: Time to accelerate from 72-105 km/h (45-65 mph); P denotes "passing acceleration."

These measures are reported by Consumer Reports magazine based on their own testing, and are the same measures that were previously investigated for a more limited sample of vehicles by Santini & Anderson (*3*).

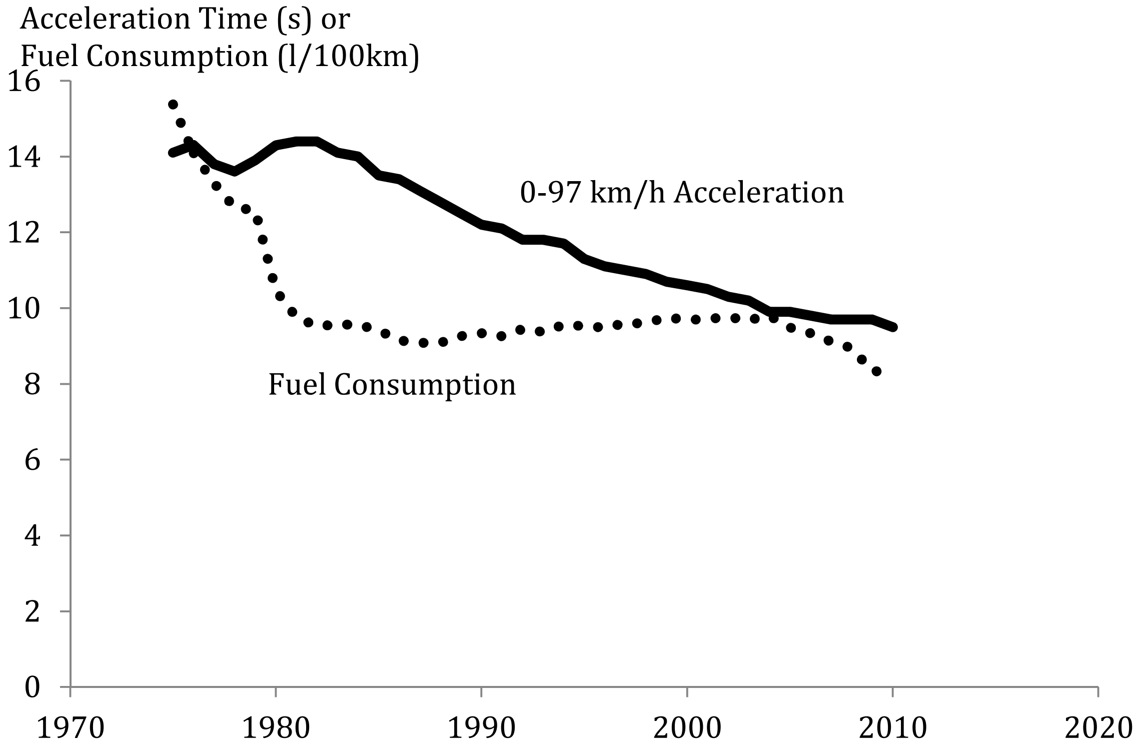

Figure 1: Average 0-97 km/h acceleration times and average unadjusted fuel consumption for new U.S. automobiles, 1975-2010, as reported by U.S. EPA (*2*). The actual rate of reduction in acceleration times has been faster than shown here.

Despite the importance of acceleration performance, a key challenge to incorporating it into analytical work is that comprehensive databases containing standardized measurements of acceleration for the whole population of vehicles are difficult or impossible to find, especially for the investigator who also requires reliable data on other vehicle attributes, sales volumes, and the like. For these investigators, detailed simulation of vehicle performance may be neither necessary nor practical. Instead, a convenient means to estimate vehicle acceleration performance based on other characteristics is desirable. To this end, many authors rely on a correlation that was originally published in 1976 for estimating a vehicle's acceleration performance based on its power-to-weight ratio (*4*). This correlation continues to be used in academic papers (*5*), reports (*6, 7*), and government data like those summarized in Figure 1 (*2*). These government data are themselves used as the basis for analyses of acceleration trends (*8, 9*). One objective of this work was to develop an improved method for estimating acceleration performance, which would be more applicable to modern vehicles and more robust over time. A second objective was to quantify the changes in acceleration performance that are not captured by the power to weight variable that underpins the estimates shown in Figure 1 and is used elsewhere.

Malliaris, Hsia & Gould (*4*) estimated a model for predicting the 0-97 km/h acceleration time using the following form, where P is engine peak power, IWT is the inertia weight, and F and f are constants:

$$Z97 = F\left(\frac{P}{IWT}\right)^{-f} \quad (1)$$

They noted the importance of many factors other than the power to weight ratio for determining acceleration performance, such as drivetrain characteristics and the engine's torque curve. However, they argued, the power to weight ratio "is overwhelmingly influential and allows by itself and adequate description of the acceleration performance." They estimated different values of the parameters F and f for vehicles with manual transmissions and for those with automatics, using acceleration times reported in the automotive enthusiast literature (e.g. *Car & Driver* magazine) for model years 1974 and 1975.

Young (*10*) updated the analysis of Malliaris, Hsia, & Gould, using performance data for model years 1989-1990 from similar sources in the automotive enthusiast literature. She investigated several functional forms, including linear forms, and considered the inclusion of engine displacement and axle ratio as additional explanatory variables. The linear models produced inferior goodness of fit, and Young concluded that the best model was one with the same form as that advanced by Malliaris, Hsia, & Gould (Equation 1), though she recommended eliminating the distinction between automatic and manual transmissions.

Santini & Anderson (*3*) improved upon the methods of the earlier investigators in several key ways. First, they noted that the functional forms used by the earlier authors placed unnecessary constraints on parameter values, by requiring that the exponent for power be the negative of the exponent for weight. They therefore adopted a more general functional form, noting that the model shown in Equation 1 is a highly restricted form of their model, where CWT is the curb weight, D is the engine displacement, A is a surrogate for frontal area, C is a dummy variable that takes the value 1 if the vehicle is a car and 0 otherwise, V is a dummy variable taking the value 1 if the vehicle is a van and 0 otherwise and X is a vector of dummy variables corresponding to a variety of engine technology packages:

$$\ln(ACC) = \beta_0 + \beta_1 \cdot \ln(P) + \beta_2 \cdot \ln(CWT) + \beta_3 \cdot \ln(D) + \beta_4 \cdot \ln(A) + \beta_5 \cdot C \cdot \ln(A) + \beta_6 V \cdot \ln(A) + \vec{\beta}\vec{X} + \varepsilon \quad (2)$$

Santini & Anderson also argued that relying on the varied sources in the automotive enthusiast literature could be problematic because of inconsistency in the testing methods used. To address these concerns, they relied on performance testing data reported by a single publication, Consumer Reports, for 107 vehicles from model years 1986-1988.

Santini & Anderson found that in addition to power and weight, important determinants of acceleration performance included engine displacement, transmission type, body type, and frontal area. They found that with few exceptions, the inclusion of specific engine technologies did not significantly affect acceleration performance after controlling for the major attributes listed above.

This paper reports work that builds on Santini & Anderson's approach by employing a much broader data set spanning 1975-2010, while estimating fixed effects for year. These changes have two important consequences. First, they make the model more appropriate for estimating vehicle acceleration performance over a wide range of years. Second, the fixed effects can be interpreted as quantifying improvements in how effectively a vehicle transforms engine power into the acceleration of the vehicle's mass. The results here indicate that for a given level of engine power and vehicle mass (and controlling for a variety of powertrain and body characteristics) contemporary vehicles deliver approximately 20% faster acceleration times from 0-97 km/h and 72-105 km/h than a typical new vehicle in 1977. Contemporary vehicles deliver about 30% faster acceleration times from 0-48 km/h than did a typical new vehicle in 1977, all else being equal. The results also indicate that most of these gains occurred prior to 1990.

The paper is organized as follows: Section 2 describes the form of the linear regression model used to estimate the various measures of acceleration. Section 3 describes the data set that was used to fit the model. Section 4 contains the results of the model estimation, and discussion of the estimated parameter values. Section 5 discusses concerns over bias in the sample of vehicles selected for acceleration testing and applies the model in order to examine trends in the 0-97 km/h acceleration performance of U.S. vehicles since 1978. Section 6 summarizes some conclusions that can be drawn from the work.

2. METHODOLOGY

In this work, a variety of model specifications were investigated, all of which use a general form similar to that advanced by Santini & Anderson. In its most unrestricted form (i.e. including all explanatory variables), the model used in this work is:

$$\begin{aligned}\ln(ACC_{it}) = {} & \beta_0 + \beta_1 \cdot \ln(P_{it}) + \beta_2 \cdot \ln(WT_{it}) + \beta_3 \cdot \ln(D_{it}) \\ & + \beta_4 \cdot [\ln(P_{it})]^2 + \beta_5 \cdot [\ln(WT_{it})]^2 + \beta_6 \cdot \ln(P_{it}) \cdot \ln(WT_{it}) + \beta_7 \cdot \ln(P_{it}) \cdot \ln(D_{it}) + \beta_8 \cdot TSpd_{it} \\ & + \vec{\beta}_T \vec{X}_{it}^T + \vec{\beta}_{P,T} \cdot \ln(P_{it}) \cdot \vec{X}_{it}^T + \vec{\beta}_E \vec{X}_{it}^E + \vec{\beta}_{P,E} \cdot \ln(P_{it}) \cdot \vec{X}_{it}^E + \vec{\beta}_D \vec{X}_{it}^D + \vec{\beta}_B \vec{X}_{it}^B + \vec{\beta}_Y \vec{X}_t^Y + \varepsilon_{it}\end{aligned} \quad (3)$$

In the above model, ACC is the acceleration metric being modeled, P is engine peak power, WT is vehicle weight (both curb weight and inertia weight were investigated), D is engine displacement, and TSpd is the number of transmission speeds (defined as zero for continuously variable transmissions). X^T is a set of dummy variables for transmission type, X^E is a set of dummy variables for engine type, X^D is a set of dummy variables for drive type, and X^B is a set of dummy variables for body style. β_T, β_E, β_D, and β_B are vectors of fixed effects capturing the average effects of dummy variables X_T, X_E, X_D, and X_B, respectively. The term X^Y is a set of dummy variables equal to 1 for year t and 0 for all other years. Thus, β_Y represents a vector of fixed effects estimating acceleration performance in each year relative to a base year, similar to the approach employed by Knittel (*5*) in estimating technological progress for U.S. automobiles. Additional terms are included to test for interaction effects of power with weight, displacement, transmission type, and engine type. The last term, ε, is an error term representing random variation due to factors not captured by the independent variables. The subscript i is an index for each vehicle observation, and the subscript t denotes the model year of the vehicle.

Several restricted versions of the above model were also estimated. Although multiple specifications were investigated, results are presented in this paper only for one model specification for each acceleration metric.

3. DATA

The database used in the present work includes approximately 1,500 vehicles that were offered for sale in the U.S. between model years 1975 and 2010 and were tested by Consumer Reports. Personal communications with both the Director of Consumer Reports' Auto Test Center and the Director of Testing for Edmunds.com suggested that inconsistency in testing methods, as noted by Santini & Anderson (*3*), continues to be an issue today, especially among enthusiast publications which compete to report the most aggressive performance numbers. As such, this work relies on testing by a single publication to eliminate the effects of this testing variation. The database includes a variety of engineering attributes and performance metrics, which include:

- Curb weight
- Engine peak power, displacement, and type (naturally aspirated gasoline, turbodiesel, etc.)
- Transmission type and number of speeds
- Drive type (rear-, front-, four- or all-wheel drive)
- Body style (sedan, SUV, etc.)
- Acceleration performance from 0-48, 0-97, and 72-105 km/h (0-30, 0-60, and 45-65 mph)

The Consumer Reports database is not a random sample of vehicles offered in the U.S. Instead, its membership is based on the decisions of Consumer Reports' staff as to which vehicles they will test. Nevertheless, the average weight and power characteristics of the vehicles tested by Consumer Reports track reasonably well with the average characteristics of all new vehicles sold in the U.S., as shown in Figure 2. Figure 2 does suggest that prior to 1990, Consumer Reports was somewhat biased toward testing lighter and less powerful vehicles. Personal communication with the Director of Consumer Reports' Auto Test Center indicated that Consumer Reports tends to test vehicles and vehicle configurations that they expect will be high-volume sellers, and which have recently undergone a redesign or refresh. The bias toward recently redesigned models may contribute to the lower average weight and power in the Consumer Reports sample in the earlier years, when power and weight were declining quickly, since overall market averages will tend to lag changes among vehicles that have been redesigned more recently. The issue of bias in the tested sample is discussed further in Section 5.

In light of its large size, the database was divided into a calibration set and a holdback set. The holdback set was used to evaluate the robustness of different model specifications to changes in the data and to assess the ability of each model specification to predict acceleration performance of vehicles not included in the calibration set. Twenty percent of the observations were randomly assigned to the holdback set, while the remaining 80 percent of the observations were used to fit the models.

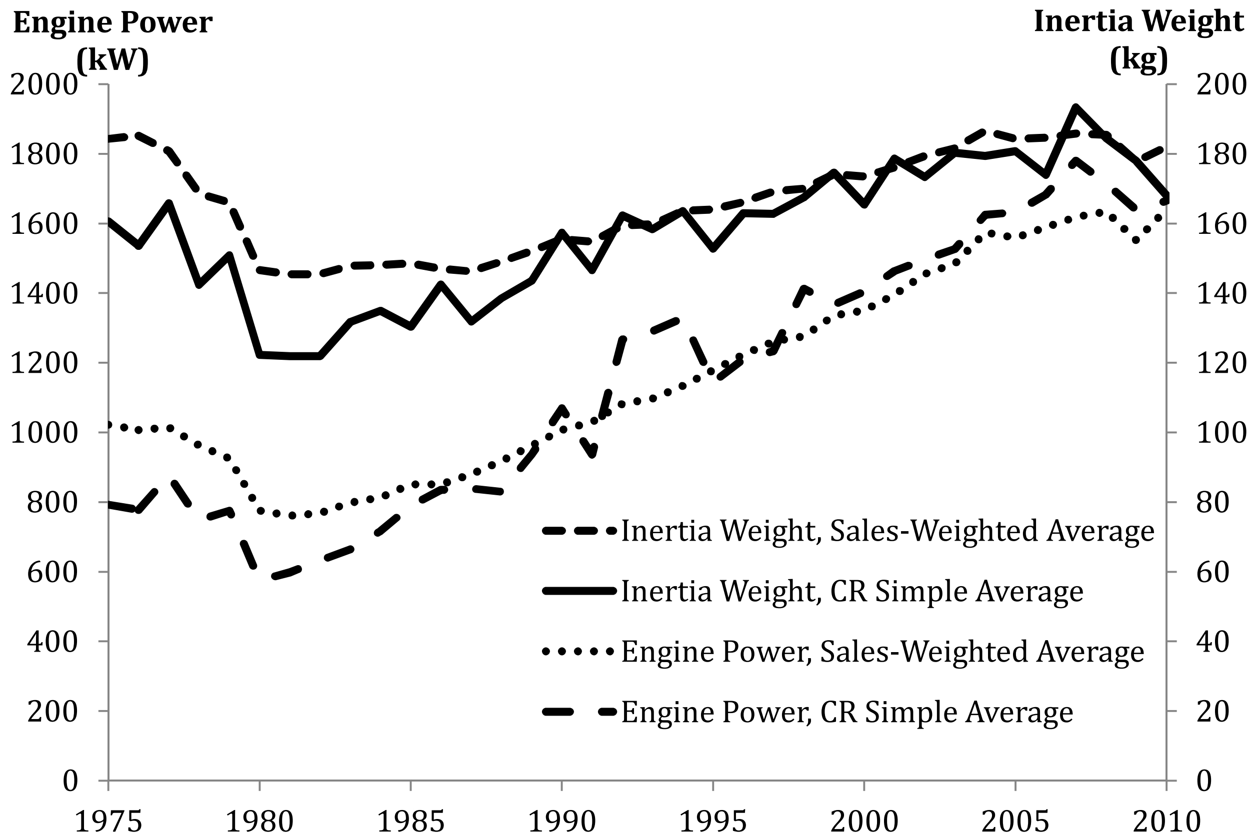

Figure 2: Inertia weight and engine power trends since 1975. Shown are simple averages for the vehicles tested by Consumer Reports (CR), which were used in fitting the model reported in this paper. Also shown are sales-weighted averages for new U.S. light-duty vehicles as reported by U.S. EPA (*2*).

4. RESULTS

Multiple model specifications were estimated, but in the interest of brevity, only one specification is reported in detail here for each acceleration metric. Other specifications distinguished between automatic transmissions and automated manuals (no significant difference), between all- and four-wheel drive (no significant difference), and/or included a dummy variable for convertibles (convertibles were slightly faster than standard cars from 0-48 and 0-97 km/h). Parameter estimates were generally stable across the different specifications. In all cases, the inclusion of the additional variables improved the model's adjusted r-squared by less than 0.001. A model specification using inertia weight instead of curb weight was also investigated, and returned marginally worse (by 0.003-0.006) adjusted r-squared values. All model specifications performed well at predicting acceleration performance in the holdback data set. Interested readers are invited to contact the authors for details of the additional specifications investigated.

Regression results for one of the investigated specifications are presented in Table 1 and Table 2. Table 1 each lists the parameter estimates and standard errors for the engineering and design attributes, including power, weight, and powertrain and body characteristics.

Table 2 summarizes the estimated fixed effects for year, which represent the expected difference between the value of the dependent variable (log of acceleration time) in each year and its value in a base year, all else being equal. The base year was defined as 1977, the first year for which all three acceleration metrics were available.

The results in Table 1 include estimates for the effects of the square of the power term, which in all three cases indicates that the sensitivity of acceleration to engine power decreases as power increases. For example, a 1% increase in power in a 75kW (100 hp) vehicle is expected to produce a 0.70% reduction in 0-97 km/h acceleration time, whereas a 1% increase in power on a 300 kW (400 hp) vehicle is expected to produce just a 0.58% reduction in the 0-97 km/h time. Also investigated, but not reported here, were model specifications that included squared weight terms, power interacted with weight, power interacted with displacement, and power interacted with the dummy variables for engine type and transmission type. With the exception of the squared term for power, none of these proved to be significant or to improve model fit, and so are not reported here.

The estimated coefficients for power, weight, displacement, and automatic versus manual transmissions are generally similar to those estimated by Santini & Anderson (*3*). The coefficients estimated here suggest that 0-48 km/h acceleration is a little more sensitive to peak power and less sensitive to curb weight and displacement than was indicated by the results of Santini & Anderson. They also indicate that the 0-97 km/h and 72-105 km/h acceleration times are less sensitive to peak power, curb weight, and displacement than indicated by their results.

TABLE 1: Regression Results for Logs of Acceleration Times. P is in kW, CWT is in kg, D is in Liters, and Continuously Variables Transmissions (CVTs) are Defined as Having Zero Speeds.

	LN(Z48)	LN(Z97)	LN(P72105)
Intercept (β_0)	1.236 *** (0.370)	2.070 *** (0.298)	2.609 *** (0.365)
ln(P)	-0.815 *** (0.139)	-1.088 *** (0.112)	-1.386 *** (0.138)
$[\ln(P)]^2$	0.046 ** (0.014)	0.044 *** (0.012)	0.074 *** (0.014)
ln(CWT)	0.483 *** (0.037)	0.665 *** (0.031)	0.620 *** (0.037)
ln(D)	-0.171 *** (0.020)	-0.121 *** (0.016)	-0.101 *** (0.020)
TSpd	-0.035 *** (0.005)	-0.031 *** (0.004)	-0.022 *** (0.005)
Transmission Types			
Manual	-0.081 *** (0.010)	-0.045 *** (0.008)	-0.052 *** (0.010)
CVT	-0.109 *** (0.032)	-0.185 *** (0.026)	-0.168 *** (0.032)
Engine Types			
Turbochg. Gasoline	-0.071 *** (0.013)	-0.066 *** (0.011)	-0.081 *** (0.013)
Superchg. Gasoline	-0.041 (0.034)	-0.059 * (0.028)	-0.073 * (0.034)
Diesel	0.122 *** (0.027)	0.116 *** (0.022)	0.158 *** (0.027)
Turbodiesel	0.029 (0.029)	-0.029 (0.024)	-0.086 ** (0.030)
Hybrid Electric	-0.023 (0.026)	-0.023 (0.022)	-0.036 (0.026)
Drive Types			
Rear-Wheel Drive	-0.011 (0.008)	0.005 (0.007)	0.023 ** (0.008)
All / 4-Wheel Drive	-0.024 * (0.012)	0.019 + (0.010)	0.031 ** (0.012)
Body Styles			
Wagon	0.029 ** (0.011)	0.019 * (0.009)	0.022 * (0.010)
SUV	0.019 (0.013)	0.019 + (0.011)	0.038 ** (0.013)
Van	0.024 + (0.014)	0.042 *** (0.012)	0.063 *** (0.014)
Pickup	0.026 (0.016)	0.031 * (0.013)	0.056 *** (0.016)
Adjusted R^2	0.8782	0.9408	0.9180

+ significant at 0.1 level ** significant at 0.01 level
* significant at 0.05 level *** significant at 0.001 level

TABLE 2: Estimated Fixed Effects of Year on Logs of Acceleration Times, Normalized to Zero in 1977.

Year	LN(Z48)	LN(Z97)	LN(P72105)
1975	NA	0.02	0.00
1976	NA	0.01	0.03
1977	0.00	0.00	0.00
1978	0.00	0.02	-0.01
1979	-0.05	-0.01	-0.02
1980	-0.07	0.00	-0.01
1981	-0.08	0.01	0.02
1982	-0.04	0.07	0.07
1983	-0.11	-0.02	-0.04
1984	-0.14	-0.02	-0.03
1985	-0.14	-0.03	-0.07
1986	-0.21	-0.08	-0.10
1987	-0.16	-0.06	-0.09
1988	-0.18	-0.06	-0.08
1989	-0.18	-0.09	-0.15
1990	-0.24	-0.15	-0.20
1991	-0.30	-0.15	-0.14
1992	-0.30	-0.17	-0.17
1993	-0.31	-0.17	-0.18
1994	-0.31	-0.18	-0.18
1995	-0.31	-0.15	-0.16
1996	-0.31	-0.17	-0.17
1997	-0.33	-0.17	-0.18
1998	-0.30	-0.15	-0.17
1999	-0.30	-0.15	-0.18
2000	-0.36	-0.19	-0.20
2001	-0.39	-0.21	-0.22
2002	-0.37	-0.19	-0.20
2003	-0.38	-0.20	-0.22
2004	-0.39	-0.20	-0.21
2005	-0.38	-0.20	-0.20
2006	-0.37	-0.20	-0.22
2007	-0.35	-0.20	-0.22
2008	-0.34	-0.18	-0.20
2009	-0.37	-0.20	-0.23
2010	-0.36	-0.19	-0.23

NA: 0-48 km/h acceleration data not reported for 1975-1976

Effects of Body Type

The various types of light trucks are estimated to deliver marginally slower acceleration than cars at low speeds, and significantly slower acceleration at higher speeds. This is consistent with trucks suffering from larger aerodynamic losses due to their higher drag coefficients and larger frontal areas. While the aerodynamic losses may not be important at low speeds, they can become considerably more important at higher speeds.

The estimated coefficients for the dummy variables representing different body types are smaller than those found by Santini & Anderson. In most cases, but not all, they are directionally the same. Santini and Anderson estimated the effect of vehicle body type using a dummy for vehicle type interacted with the logarithm of frontal area in m^2, as shown here for vans:

$$BodyTypeEffect = \beta \cdot \ln(FrontalArea) \cdot Van \quad (4)$$

The data set used in this work did not include frontal area, so effects were estimated for vehicle type dummy variables without including frontal area:

$$BodyTypeEffect = \beta' \cdot Van \quad (5)$$

Thus, the coefficient estimates from this work are more appropriately compared with the logarithm of the frontal area from Santini & Anderson's results, appropriately interacted with their dummy variables for body type. For model year 2008, the logarithm of the frontal area in m^2 ranged from 0.8-1.2 for cars, from 1.0-1.6 for pickups and SUVs, and from 1.2-1.8 for vans.

Based on the ranges noted above, the combined effects of size and body type from Santini & Anderson's work suggest the following:

- Pickups and SUVs have similar 0-48 km/h acceleration to cars, while vans have slightly faster acceleration times,
- Vans do slightly worse, and SUVs and pickups do considerably worse than cars accelerating from 0-97 km/h, and
- SUVs, vans, and pickups all have considerably worse acceleration than cars from 72-105 km/h.

In contrast, the results presented in this work suggest that SUVs, pickups, and vans all have somewhat slower acceleration than cars, with the effect less pronounced for SUVs. In addition, the magnitudes of the estimates reported here are smaller than the combined size & body type effects reported by Santini & Anderson.

Effects of Drivetrain Characteristics

The parameter estimates reported in Table 1 indicate that a manual transmission delivers approximately 8% faster acceleration times from 0-48 km/h and approximately 4-5% faster acceleration times from 0-97 km/h and 72-105 km/h than are obtained with an automatic transmission. Care must be taken when interpreting the coefficients for continuously variable transmissions (CVTs), because CVTs were defined as having zero speeds. Thus, the effects for CVTs must be compared against the combined effects of transmission type and number of transmission speeds for automatic or manual transmissions. For example, although the coefficient for CVTs is estimated at -0.185 according to the results for 0-97 km/h acceleration in Table 1, the expected 0-97 km/h acceleration time for a vehicle with a CVT would only be about 3% faster than an identical vehicle equipped with a 5-speed automatic transmission:

$$\ln(Z97_{CVT}) - \ln(Z97_{Auto-5}) = \beta_{CVT} - \beta_{TSpeeds} TSpeeds = -0.185 - (-0.031) \cdot (5) = -0.03$$

The parameter estimates indicate that turbo- and supercharged gasoline vehicles deliver faster acceleration than naturally aspirated engines, all else being equal. However, caution should be exercised in interpreting these coefficients because a boosted engine can be expected to have a smaller displacement than a naturally aspirated engine delivering the same peak power. Because the models investigated here separately control for displacement, boosting and downsizing an engine to achieve the same peak power will incur two offsetting effects on predicted acceleration performance: a decrease in acceleration time due to boosting and an increase due to smaller displacement. For example, consider a vehicle with an engine that has been downsized by 30% and turbocharged so as to maintain the original peak power. Assuming that vehicle weight remains unchanged, the parameter estimates reported in Table 1 predict that these changes would result in 1%, 2%, and 4% net reductions in the acceleration times from 0-48 km/h, 0-97 km/h, and 72-105 km/h, respectively.

The results indicate that hybrid electric powertrains do not deliver significantly different acceleration performance than conventionally powered vehicles with the same peak power. It is worth noting here that the data set from Consumer Reports lists combined system power for hybrids, rather than engine power only. Hybrid designations were made by Consumer Reports, and this analysis did not distinguish any further between different types of hybrids. There were 20 hybrids in the data set: 8 Toyota & Lexus, 3 Ford & Mercury, 1 Nissan, 5 Honda, and 3 GM (2007 Vue Greenline, 2009 Malibu, 2008 Tahoe).

Naturally aspirated diesels, which are not found in the data set for years later than 1982, delivered significantly slower acceleration performance than similar gasoline engine vehicles. Turbodiesels are estimated to deliver similar to s faster performance than conventional gasoline engine vehicles.

Rear-wheel and front-wheel drive vehicles are estimated to deliver similar acceleration performance, with rear-drive vehicles delivering slightly faster passing acceleration. Four-and all-wheel drive vehicles deliver faster acceleration up to 48 km/h, which may be due to reduced wheel spin in high-powered vehicles. However, this advantage is reversed at higher speeds, consistent with increased driveline losses and the reduced importance of wheel slip as a limiting factor at higher speeds.

Effects of Time

The fixed effects estimated for each year can be interpreted as a measure of how much more effectively a vehicle transforms engine power into acceleration performance for a vehicle of a given mass, controlling for a variety of other vehicle characteristics. Knittel (*5*) used fixed effects for year in a similar way, interpreting them as a measure of technological progress for vehicle technology in a broad sense. An analogous interpretation can be made here, with the fixed effects capturing technological improvements that are not represented in the Consumer Reports data. Such improvements may include better aerodynamics, reduced tire rolling resistance, and increased efficiency of powertrain components downstream of the engine. These improvements would reduce the engine power devoted to overcoming losses, which would free up more power to accelerate the vehicle. Another possibility is that improvements in tire technology have reduced wheel slip, a hypothesis that is consistent with the result (discussed below) that 0-48 km/h acceleration has shown larger relative improvements than 0-97 km/h and 72-105 km/h acceleration. Regardless of the particular sources of the improvements, it does appear that engineers today are able to obtain higher performance per unit of power (and weight, etc.) than they could in the past.

For small values, the year fixed effects are approximately equal to a percentage change in acceleration time. For example, a year fixed effect of -0.01 indicates that a vehicle is expected to deliver approximately a 1% faster acceleration time than a comparable vehicle in the base year. For larger values of the fixed effects, nonlinearities become significant, but the fixed effects can be transformed into a ratio of expected acceleration time for a vehicle relative to a comparable vehicle in the base year. Assuming all independent variables other than the year fixed effect to be equal in year t and in some base year, and normalizing the fixed effect to be zero in the base year, one can subtract Equation 3 for the base year from Equation 3 for year t to obtain:

$$\ln(ACC_t) - \ln(ACC_{Base}) = \beta_{Y,t} - \beta_{Y,Base} = \beta_{Y,t} \qquad (6)$$

Where $\beta_{Y,t}$ is the year fixed effect for year t. By rearranging Equation 6, it is clear that the year fixed effect can be transformed into the ratio of the expected acceleration time for a given vehicle in year t to the expected acceleration time of a similar vehicle in the base year:

$$\frac{ACC_t}{ACC_{Base}} = e^{\beta_{Y,t}} \qquad (7)$$

The estimated fixed effects of year were approximately the same in all model specifications, but did vary between the different measures of acceleration time. The variation between different metrics of acceleration is illustrated in Figure 3, which plots the expected acceleration times in each year relative to a base year of 1977, using the fixed effects estimated from the models reported in this paper. Several features visible in the figure are worthy of attention.

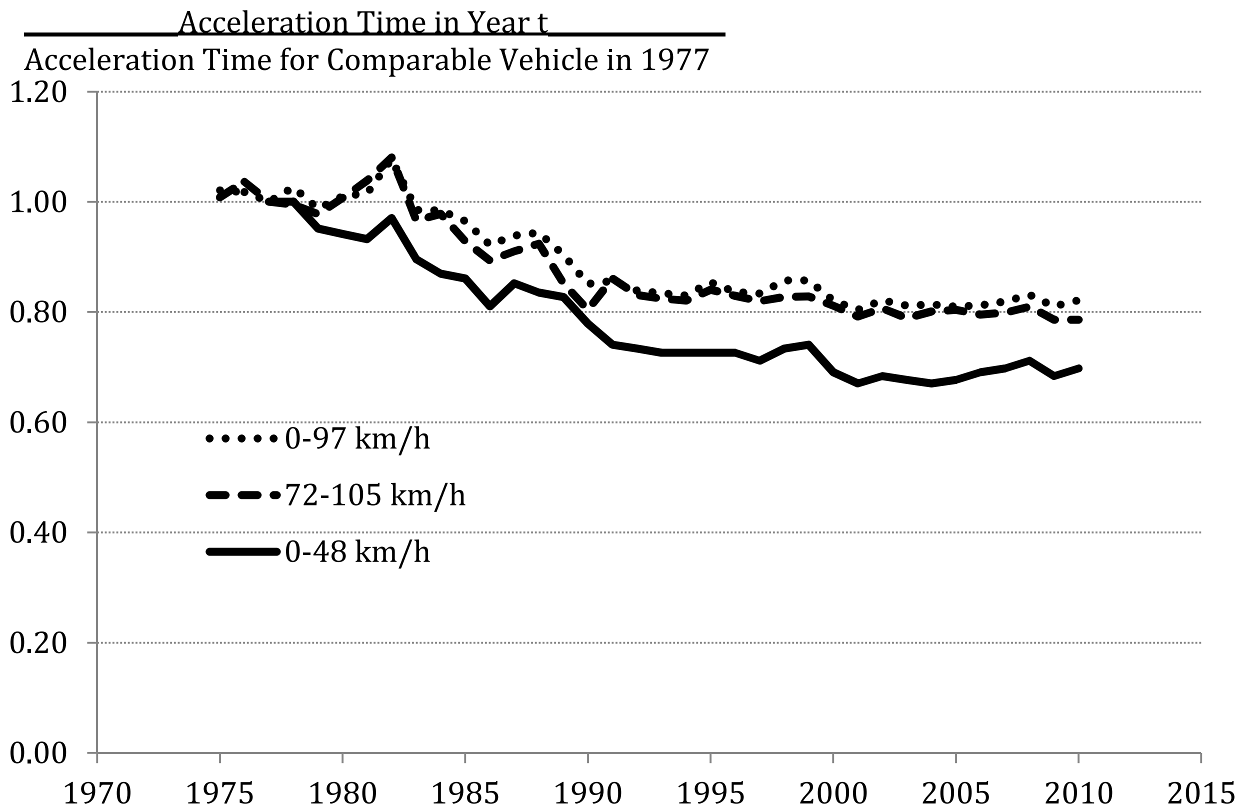

Figure 3: Ratio of expected acceleration time for a vehicle in each year to that of a comparable vehicle (i.e. same power, weight, transmission type, etc.) in 1977. Relative reductions in 0-48 km/h acceleration times have been greater than those in 0-97 km/h and 72-105 km/h acceleration times.

First, it is clear that the expected acceleration performance of a vehicle, conditioned on engine power, vehicle weight, and a number of other attributes, is considerably faster today than it was in the 1970s. As discussed previously, this can be interpreted as representing technological progress that has improved the ability of vehicles to squeeze more useful performance from a given level of power.

Second, the rate of change in acceleration performance, conditioned on other attributes, has not been uniform. Rapid improvements through the 1980s were followed by more gradual changes since 1990. This observation is generally consistent with findings that the overall rate of technical improvement in U.S. light-duty vehicles was most rapid in the early 1980s and has slowed down in more recent years (*5*).

Third, the estimates suggest that 0-97 and 72-105 km/h acceleration may have deteriorated between the late 1970s and early 1980s, while lower-speed acceleration performance (i.e. 0-48 km/h) did not. However, the statistical significance of the year fixed effects through 1985 is marginal at best, and it is impossible to conclude with any confidence that the 0-97 and 72-105 km/h acceleration performance (conditioned on other attributes) actually deteriorated during this time.

Finally, the estimates do show that the relative improvements in the 0-48 km/h acceleration have been larger than those in the 0-97 and 72-105 km/h acceleration. It is not possible to say from the available data what the reason is for the difference between these rates of improvement, but several explanations are plausible and could be investigated if a richer data set were available. First, the difference may be due to improvements in throttle response, which would improve acceleration "off the line." This would have a larger relative effect on the 0-48 km/h acceleration than on the higher speed acceleration measures. Second, improvements in tire technology that reduce wheel slip would be expected to have a larger effect at lower speeds, where wheel slip is more likely to be a limiting factor in acceleration. Finally, market forces might have driven a greater emphasis on acceleration performance at lower speeds than at higher speeds. These demands could be met, for example, by altering gear ratios to favor low-speed performance. However, changing the ratios in lower gears would not necessarily improve acceleration at higher speeds, and could even compel tradeoffs that reduce acceleration performance at higher speeds.

5. APPLYING THE MODEL TO NEW DATA SETS

The predictive ability of each model specification was assessed using the holdback data set. The prediction errors were generally similar across different model specifications, and increased slightly as the adjusted r-squared values fell. Applying the models to the holdback data suggested that there were no surprises associated with making predictions from any of the model specifications. Any of the specifications, including those reported here, appear to be appropriate for predicting acceleration performance.

Representativeness of the Consumer Reports Sample

As noted in Section 2, the sample of vehicles tested by Consumer Reports is not randomly selected from the population of vehicles available on the market. This raises concerns about possible bias in the estimates of the regression coefficients, and the applicability of the models to vehicles not tested by Consumer Reports. To address these concerns, propensity scores were estimated for the likelihood of a vehicle being included in Consumer Reports' testing program, conditional on a variety of vehicle characteristics. The estimated propensity scores were then incorporated into the regression analyses using two approaches outlined by Schafer & Kang (*11*).

Propensity scores were estimated by fitting a logit model of the probability of a vehicle being included in the Consumer Reports' testing program. The model included as predictor variables vehicle class, power, weight, powertrain characteristics, manufacturer, model year, and a variety of interactions among these. There was good overlap between the propensity scores in the population and those in the Consumer Reports sample.

Next, dummy variables were defined for the deciles of propensity scores, and these were included these as additional regressors in the models. The dummy variables were generally insignificant, and the estimates of the coefficients and year fixed effects remained essentially unchanged when compared with the models that did not include the propensity scores.

In an alternative approach, the regressions were weighted by the inverses of the propensity scores. The rationale for this approach is that it can weight the observations in the sample by the number of vehicles that they represent in the full population. This procedure led to increases in the estimated sensitivity of acceleration times to power and to weight, and to some slight changes in the coefficient estimates on the dummy variables for powertrains, body types, and other vehicle characteristics. However, the weighting did not change the general trends or levels of the year fixed effects, but did increase their volatility from year to year.

Finally, both the weighted and unweighted regression models were applied to the holdback data set. In all cases, the weighted regression model returned larger average errors than the unweighted regression model (including when errors were averaged by the inverse propensity score). Based on these findings, it is recommended that the coefficient estimates from the unweighted regression model be used, even if applying the models to the full population of vehicles.

Implications of Results for Estimates of U.S. Vehicle Performance

The results reported in this work suggest that the acceleration performance of new U.S. vehicles has been improving more quickly than previously thought. Figure 4 shows the sales-weighted average 0-97 km/h acceleration times calculated by applying the model reported to a comprehensive database of vehicle attributes and sales volumes spanning 1978-2009, as well as the average acceleration calculated by applying the more typical method of Malliaris, Hsia, & Gould (*4*). Also shown are the average acceleration values reported by U.S. EPA (*2*) for 1975-2010. The latter agree very closely with the results obtained using the Malliaris, Hsia, & Gould method, suggesting that there are only small discrepancies between the database used here and that used by EPA. Over the last four years, the average acceleration calculated using the Malliaris, Hsia, & Gould method has been approximately 0.9 seconds, or 10%, greater than the average of 8.8 seconds calculated using the model reported in this work. Between 1982 and 2009, the estimated average 0-97 km/h acceleration time of new U.S. vehicles decreased from 16.6 seconds to 8.8 seconds. Over the same period, the average 0-48 km/h acceleration time decreased from 5.5 seconds to 3.9 seconds, and the average 72-105 km/h passing acceleration time fell from 10.9 seconds to 7.2 seconds.

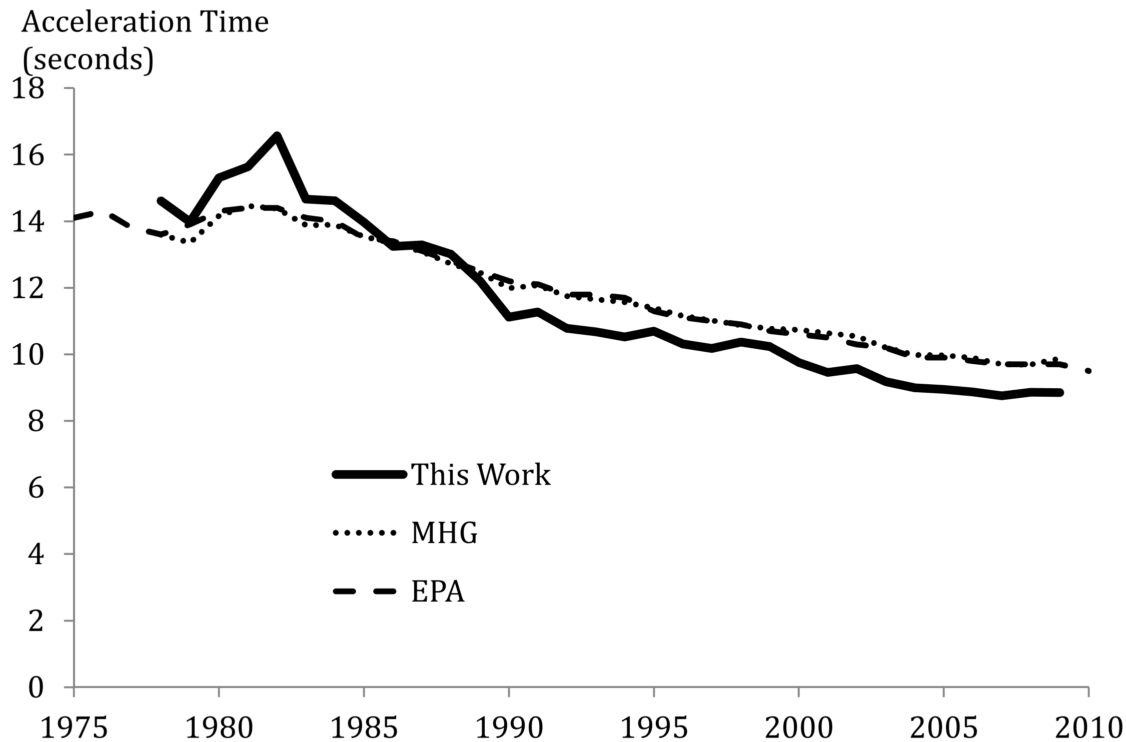

Figure 4: Sales-weighted average 0-97 km/h acceleration times calculated by applying method of Malliaris, Hsia, & Gould (*4*) and the model reported in this work to vehicle attribute and sales data for 1978-2009. Also shown are the averages reported by U.S. EPA (*2*) for 1975-2010.

Reductions in 0-97 km/h acceleration times are observed within high-performance and low-performance vehicles alike. Figure 5 shows how 0-97 km/h acceleration times have changed since 1978 for the median vehicle as well as for vehicles at the fastest and slowest ends of the market. In this case, the high-performance end of the market is represented by the 5^{th} percentile vehicle, i.e. the one that is slower than 5% of vehicles in its model year, based on sales. The low-performance end of the market is represented by the 95^{th} percentile vehicle, i.e. one that is slower than 95% of vehicles in its model year, based on sales.

Two features of Figure 5 are especially striking. First, even the slowest vehicles today offer performance that was typical of the early 1990s, and reserved for only the fastest cars a few years earlier. Ninety-five percent of vehicles sold today achieve a level of acceleration performance that beats the average from 1992, and would have put them in the top 5% in 1985. Second, the chart shows that although acceleration times have been getting faster, the rate of change has been declining. In fact, the chart appears to suggest that acceleration performance may be approaching an asymptote.

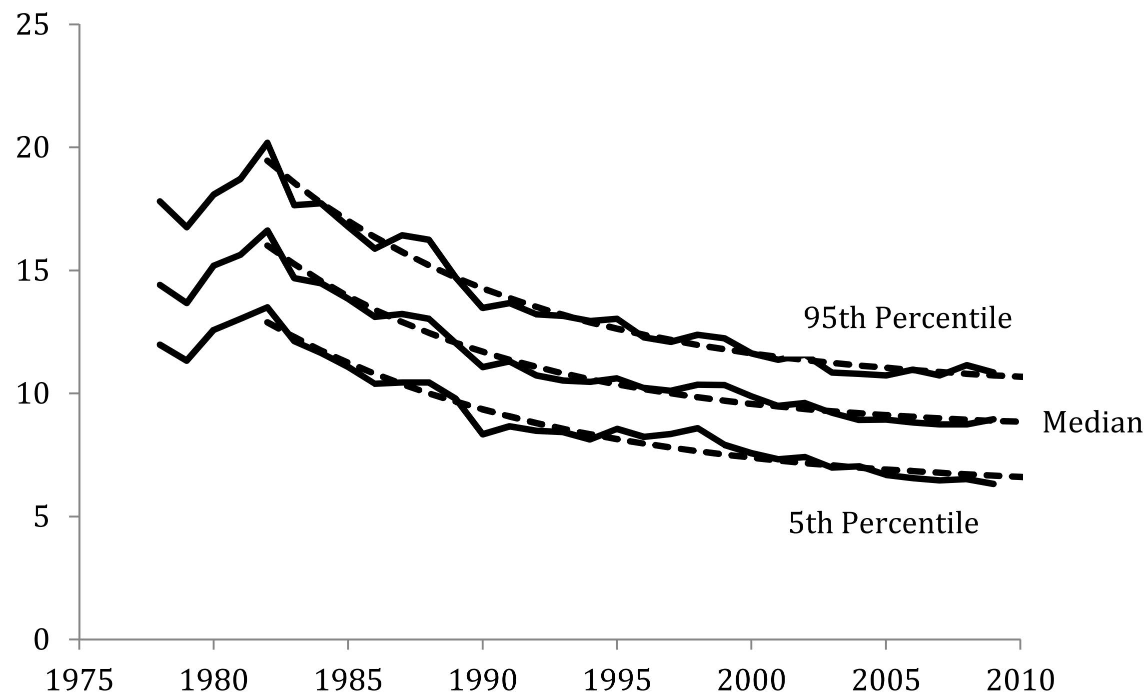

Figure 5: Median, 5th percentile, and 95th percentile times for acceleration from 0-97 km/h, as estimated using the model reported here, for 1978-2009. Also shown are curves fitted for the years 1982-2009. Reductions in 0-97 km/h acceleration times have been observed across the whole market, and trends are consistent with decay toward an asymptote.

A model of exponential decay toward an asymptote captures both the asymptotic acceleration level and the rate of approach toward that level:

$$Z97_t = a \cdot e^{b(t-1980)} + c \quad (9)$$

Parameter c in Equation 9 represents the estimated asymptotic performance level, while parameter b captures the average rate at which acceleration performance has been approaching this level, and parameter a is a constant. These parameters were estimated using least-squares estimation for the years 1982-2009, for a variety of performance levels. The curves fitted in this manner for the median, 5th percentile, and 95th percentile performance levels have been added to Figure 5. The fitted parameters suggested, firstly, that the rate of decay, b, is fairly stable regardless of whether vehicles are high-performance, low-performance, or in the middle of the pack. The smallest value of b among the performance levels investigated was -0.105, for the 50th percentile. The largest value of b was -0.086, for the 90th percentile. In addition, the estimated asymptotic performance levels ranged from 6.1 seconds for vehicles in the 5th percentile to 10.1 seconds for vehicles in the 95th percentile. It is interesting to note that even high-performance vehicles are today within one second of their estimated asymptotic values. This is, of course, far short of proof that reductions in acceleration times are going to stop any time soon, but it does at least suggest that Americans' thirst for power in their cars may in fact be quenchable.

6. CONCLUSIONS

In this work, models have been fitted for estimating the acceleration performance of light-duty automobiles, based on performance tests conducted by Consumer Reports between model years 1975 and 2010. A flexible functional form was adopted and various specifications were estimated, which controlled for vehicle attributes including powertrain characteristics and body type. It was found that power and weight are extremely important in determining acceleration performance, consistent with findings by previous investigators. Other attributes including displacement, powertrain characteristics, and body type have smaller but still significant effects on expected acceleration performance. Judging by their performance on a holdback data set, the model specifications reported here all appear to be valid for making predictions of acceleration performance.

The change in the relationship between acceleration performance and observed attributes was also estimated. All else being equal, new vehicles today were found to achieve approximately 20-30% faster acceleration times than 1970s-vintage vehicles with the same observed attributes. This improvement in acceleration was largest in the early 1980s, and the change was found to be larger for lower-speed acceleration than for higher-speed acceleration. Prior to 1990, performance improvements appear to have been driven both by increases in power and by improvements in how effectively that power is used to accelerate a vehicle. Since 1990, however, most of the performance improvements appear to be attributable to changes in power, weight, and other variables that are tracked directly in the Consumer Reports data, as the changes in fixed effects from year to year have diminished considerably.

The acceleration performance of vehicles sold in the U.S. today is even faster than is indicated by commonly reported numbers. New vehicles sold in the U.S. between 2006 and 2009 have been estimated to have an average 0-97 km/h acceleration time of 8.8 seconds, about 0.9 seconds faster than the averages reported by U.S. EPA. Interestingly, however, the changes in 0-97 km/h acceleration performance since 1982 fit very well with a model of exponential decay toward an asymptote. This pattern holds up for vehicles ranging from high-performance to low-performance, all of which appear at present to be within one second of their respective asymptotic values. This suggests that further work may be warranted to investigate whether consumers' appetites for higher performance are indeed becoming satiated.

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