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SLOAN AUTOMOTIVE LABORATORY

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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Motivation

Understanding vehicle acceleration is crucial because acceleration capabilities affect:

- ***Fuel Consumption.*** **All else being equal, faster acceleration capabilities mean higher test-cycle fuel consumption.**
- ***Purchase Decisions.*** **Consumers value acceleration performance when selecting a vehicle.**
- ***Driver Behavior.*** **Acceleration capabilities affect in-use acceleration, with implications for safety and on-road fuel consumption.[1]**

Despite the importance of acceleration performance, standardized measurements are seldom reported and acceleration is often estimated using a correlation developed in the 1970s.[2] The objectives of this work were:

1. **To develop a more complete and up-to-date method for estimating acceleration performance based on other commonly-reported vehicle attributes, and**
2. **To quantify the annual improvements in acceleration performance that are due to factors beyond basic ones like increased power-to-weight ratio, transmission type, and so forth.**

Data

This work was based on ~1,500 cars and light trucks tested by Consumer Reports magazine between 1975 and 2010. Data reported for each vehicle included:

- **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)**

80% of the observations, selected at random, were used to fit the models. The remaining observations were used as a holdback set, to test the robustness of different model specifications.

Methodology

A linear regression model was estimated, starting from the form employed by Santini & Anderson.[3] Additional terms were included to test for nonlinear and interaction effects, and to estimate fixed effects for years. The most general functional form investigated was:

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

Where:

- **ACC is the acceleration metric being modeled**
- **P is engine peak power**
- **WT is vehicle weight. Both curb weight (CWT) and inertia weight (IWT) were investigated**
- **D is engine displacement**
- **TSpd is the number of transmission speeds (defined as zero for continuously variable transmissions).**
- **X^T, X^E, X^D, and X^B are sets of dummy variables for transmission type, engine type, drive type, and body style, respectively.**

Vehicles were not selected at random from all available vehicles, but were chosen deliberately by Consumer Reports. The sample could be unrepresentative of population, leading to results that are invalid for the larger population of vehicles. Therefore, propensity scores were estimated for the likelihood of a vehicle being included in Consumer Reports' testing program. The propensity scores were used to check the model specification in two ways:

1. **Dummy variables for the propensity score decile were included as covariates in the regression**
2. **The regression was weighted by the inverses of the propensity scores**

Results

Regression results for logs of 0-48 km/h (Z48), 0-97 km/h (Z97), and 72-105 km/h (P72105) 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 ***	2.070 ***	2.609 ***
	(0.370)	(0.298)	(0.365)
ln(P)	-0.815 ***	-1.088 ***	-1.386 ***
	(0.139)	(0.112)	(0.138)
$[\ln(P)]^2$	0.046 **	0.044 ***	0.074 ***
	(0.014)	(0.012)	(0.014)
ln(CWT)	0.483 ***	0.665 ***	0.620 ***
	(0.037)	(0.031)	(0.037)
ln(D)	-0.171 ***	-0.121 ***	-0.101 ***
	(0.020)	(0.016)	(0.020)
TSpd	-0.035 ***	-0.031 ***	-0.022 ***
	(0.005)	(0.004)	(0.005)
Transmission Type			
Manual	-0.081 ***	-0.045 ***	-0.052 ***
	(0.010)	(0.008)	(0.010)
CVT	-0.109 ***	-0.185 ***	-0.168 ***
	(0.032)	(0.026)	(0.032)
Engine Type			
Turbochg. Gasoline	-0.071 ***	-0.066 ***	-0.081 ***
	(0.013)	(0.011)	(0.013)
Superchg. Gasoline	-0.041	-0.059 *	-0.073 *
	(0.034)	(0.028)	(0.034)
Diesel	0.122 ***	0.116 ***	0.158 ***
	(0.027)	(0.022)	(0.027)
Turbodiesel	0.029	-0.029	-0.086 **
	(0.029)	(0.024)	(0.030)
Hybrid Electric	-0.023	-0.023	-0.036
	(0.026)	(0.022)	(0.026)
Drive Type			
Rear-Wheel	-0.011	0.005	0.023 **
	(0.008)	(0.007)	(0.008)
All / 4-Wheel	-0.024 *	0.019 +	0.031 **
	(0.012)	(0.010)	(0.012)
Body Style			
Wagon	0.029 **	0.019 *	0.022 *
	(0.011)	(0.009)	(0.010)
SUV	0.019	0.019 +	0.038 **
	(0.013)	(0.011)	(0.013)
Van	0.024 +	0.042 ***	0.063 ***
	(0.014)	(0.012)	(0.014)
Pickup	0.026	0.031 *	0.056 ***
	(0.016)	(0.013)	(0.016)
Adjusted R^2	0.878	0.941	0.918

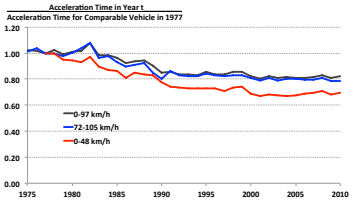
\+ significant at 0.1 level ** significant at 0.01 level
* significant at 0.05 level *** significant at 0.001 level

- **Interactions and squared terms not listed here were found not to be statistically significant.**

All else equal…

- **Net effect of a 1% increase in power is a 0.70% reduction in 0-97 km/h time for a 75kW vehicle, but 0.58% for a 300kW vehicle.**
- **CVT is about 3% faster than similar 5-speed automatic from 0-97 km/h**
- **Downsizing by 30% + turbocharging to maintain peak power yields ~2% reduction in 0-97 km/h time.**
- **All/4-wheel drive delivers better acceleration off the line (reduced wheel slip), but worse acceleration at higher speeds (increased driveline losses).**
- **A standard body style delivers the best acceleration performance.**
- **Trucks show larger penalties at higher speeds (greater aerodynamic losses).**

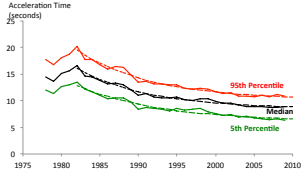
Ratios of Acceleration Times for New Vehicles in Each Year to Comparably Specified Vehicles in 1977



- **All else equal, a new vehicle today delivers 20-30% faster acceleration than a comparably-specified vehicle from the late 1970s.**
- **Most of this improvement occurred through the 1980s.**
- **Year effects can be interpreted as improvements in how effectively vehicles use a given unit of power to accelerate a given mass, capturing technological changes not represented in Consumer Reports' vehicle specifications.**

Applying Model to U.S. Vehicles

Distribution of 0-97 km/h Acceleration Times

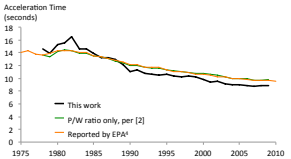


Reductions in 0-97 km/h times have been seen across all performance segments.

	5th Percentile	Median	95th Percentile
1982	13.5 s	16.6 s	20.2 s
2009	6.3 s	8.9 s	10.8 s
Estimated Asymptote	6.1 s	8.5 s	10.1 s

- **Acceleration performance that was typical in the early 1990s would put a vehicle among the slowest on offer today.**
- **Even the slowest end of the market (95th percentile) today delivers performance that was reserved for the fastest vehicles (5th percentile) in the mid-1980s.**
- **Rate of decrease in acceleration times is falling, and trends are consistent with exponential decay toward an asymptote.**

Sales-weighted Average 0-97 km/h Times



Sales-Weighted Average Acceleration Performance in 1982 and 2009

	0-48 km/h	0-97 km/h	72-105 km/h
1982	5.5 s	16.6 s	10.9 s
2009	3.9 s	8.8 s	7.2 s

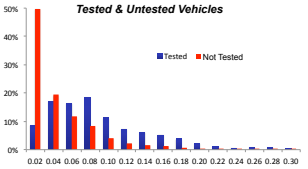
- **Reductions in average acceleration times over the last 30 years have been greater than previously reported**
- **Average 0-97 km/h acceleration of vehicles in recent years has been 0.9 seconds (10%) faster than indicated by standard analysis.**

Accounting for Sample Selection

Propensity scores were estimated for the probability of a vehicle being included in the Consumer Reports testing program, based on:

- **Vehicle class**
- **Power**
- **Weight**
- **Powertrain characteristics**
- **Manufacturer**
- **Model year**
- **Interactions among these**

Distribution of Propensity Scores: Tested & Untested Vehicles



The propensity scores were used to check the regression specification in two ways:

1. **Dummy variables for propensity score deciles were included as covariates in the regression.**
   - **Coefficients on the dummy variables for propensity score decile were statistically insignificant.**
   - **Other coefficients and year fixed effects were unchanged by the introduction of the propensity score dummy variables.**
2. **The regression was weighted by the inverses of the propensity scores.**
   - **Coefficient estimates changed modestly, especially on weight and power**
   - **Year fixed effects became more volatile**
   - **Weighted regression model yielded larger prediction errors on holdback data set**

Conclusions

- **Power and weight continue to be the most important determinants of acceleration performance.**
- **Other attributes including displacement, powertrain characteristics, and body type have smaller but still significant effects.**
- **All else being equal, new vehicles today achieve approximately 20-30% faster acceleration times than 1970s-vintage vehicles with the same observed attributes.**
- **Average acceleration performance is faster, and has changed more rapidly, than is indicated by commonly-reported numbers**
- **Acceleration times from 0-97 km/h were approximately halved between 1982 and 2009, a pattern that held up for both low-performance and high-performance vehicles.**
- **The unweighted regression results presented here are preferred for estimating acceleration performance, as accounting for sample selection did not improve model performance.**

References

1. Berry, I. The effects of driving style and vehicle performance on the real-world fuel consumption of U.S. light-duty vehicles. S.M. Thesis, Massachusetts Institute of Technology. Cambridge, MA, 2010.
2. Mallairis A.C., H. Hsia, and H. Gould. Concise description of auto fuel economy and performance in recent model years. SAE Technical Paper Series, 760045. 1976.
3. Santini D.J. and J. Anderson. Determinants of multiple measures of acceleration. SAE Technical Paper Series, 931805. 1993.
4. U.S. EPA. Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2010. Report No.: EPA-420-R-10-023. Office of Transportation & Air Quality, U.S. Environmental Protection Agency. Ann Arbor, MI, 2010.

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