A Treasure Trove of Physics from a Common Source—Automobile Acceleration Data

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What is better than interesting, challenging physics with good data free for the taking to which everyone can relate? That's what is available to anyone who digs into the reams of automobile performance tests that have been available in popular magazines since the 1950s. Opportunities to do and teach interesting physics abound, as evidenced by the frequent appearance of "physics of cars" articles in *The Physics Teacher*.[1-6]

Magazines for automobile enthusiasts regularly conduct in-depth tests of a car's acceleration ability well beyond simply a "0–60" time. A thorough car performance test conducted by a magazine such as *Road & Track* will include the weight of the car and the time it takes the car to accelerate from a standing stop to a variety of different speeds ranging from 0–20 mph all the way to, for some cars, 0–150 mph. The performance test is a physics experiment that yields time, velocity, and mass data for the accelerating automobile.

Using the mass and test speeds, and the fact that kinetic energy is given by

$$KE = ½\, mv^2, \tag{1}$$

it is easy to obtain a table of *KE*-versus-time data and graph it. This is shown in Fig. 1 for a 1984 Alfa Romeo Spider.

The plot of *KE* versus *t* is interesting because the data are linear—the power output of the car available for making the car accelerate is constant from zero through 80 mph. The slope of a line fit to the data yields the power output of the engine that is available to accelerate the car (P_A):

$$\text{Slope} = \text{rise/run} = \Delta KE/\Delta t = P_A. \tag{2}$$

In this case $P_A = 3.6 \times 10^4$ J/s = 48 hp. Rearranging the equations yields an equation for v as a function of P_A and t when given a mass m, a starting speed v_0, and a starting time t_0.

$$\Delta KE/\Delta t = P_A$$

$$(KE - KE_0)/(t - t_0) = P_A$$

$$(½\, mv^2 - ½\, mv_0^{\,2})/(t - t_0) = P_A \tag{3}$$

1984 Alfa Romeo Spider Road Test Data
Road & Track, March 1984
Test weight 2645 lbs. (mass 1201 kg)

Time (s)	Speed (mph)	Speed (m/s)	KE (J)
0.00	0	0.00	0.00
3.60	30	13.41	107967.17
11.70	60	26.82	431868.69
18.30	74	33.08	656920.26
21.60	80	35.76	767766.55

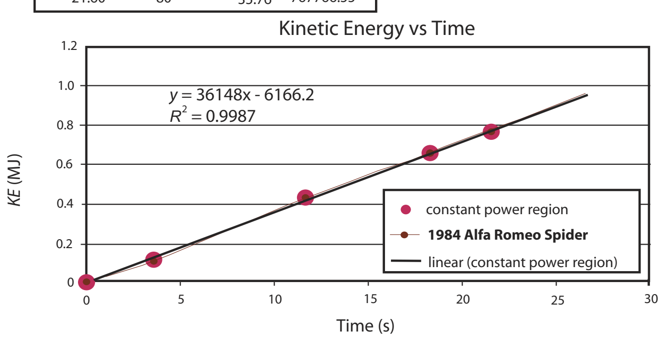

Fig. 1.

or

$$v = (2P_A\, t/m)^{1/2} \quad (4)$$

if $v_0 = 0$ at $t_0 = 0$. Plotting Eq. (4) using $P_A = 3.6 \times 10^4$ J/s and $m = 1201$ kg, one sees remarkable agreement between Eq. (4) and the original road test data for the Alpha Romeo (Fig. 2).

Note: The power available for acceleration (the only power that counts, from a performance standpoint) is virtually a constant 48 hp throughout the test. This result will surprise many readers who know that the *engine's* power output will vary considerably as its rpms rise and fall. Nonetheless, the graph of *KE*-versus t is linear. What is going on? The engine, the drive train, and various frictional factors are all combining to create a nearly constant 48 hp available to accelerate the Alpha Romero from rest through 80 mph.

Not all road tests yield perfectly linear *KE*-versus-t plots. All cars have a top speed—their *KE* versus-t-plot cannot increase linearly indefinitely. At some point the rate of increase in *KE* must drop off.

This is due to two principal factors—friction drag and engine limits. As speed increases, friction also increases from all sources (particularly air drag, where power loss will rise as the cube of speed). Also, engines have limits on how fast they can run. Problems with "valve float" (when the engine turns so fast that valves within the engine cannot fully close) and air flow (when it becomes impossible to draw sufficient air into the engine) mean that power output must eventually drop off. The Alfa Romeo never reached the point where these factors became significant, so it never approached its "top end."

In Fig. 3 we see a *KE*-versus-t plot for a 1983 Chevrolet Corvette that does show this "top end effect." For $t = 0$ to 15 s the plot is linear, with a slope indicating $P_A = 8.05 \times 10^4$ J/s = 108 hp. After that the graph begins to fall off. In the plot of v versus t the deviation from constant P_A is apparent for $t > 15$ s ($v > 100$ mph).

While some cars show deviation from a linear *KE*-versus-t plot at high speeds, other cars show deviation at low speeds when the car's acceleration run is "launched." This is seen in the *KE*-versus-t graph for a 1967 Oldsmobile Cutlass (Fig. 4). Figure 4 shows the "top end effect," but it also shows a delay between

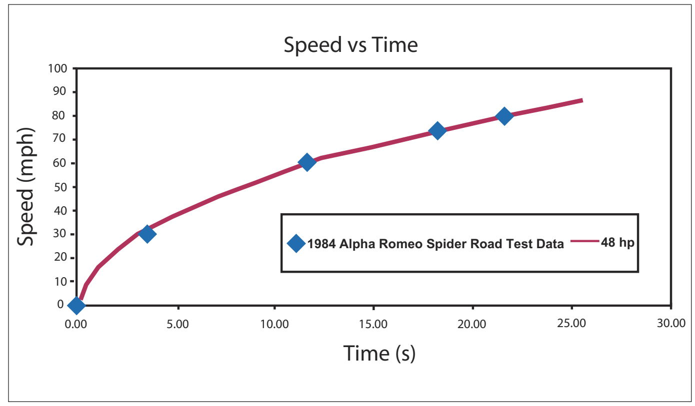

Fig. 2.

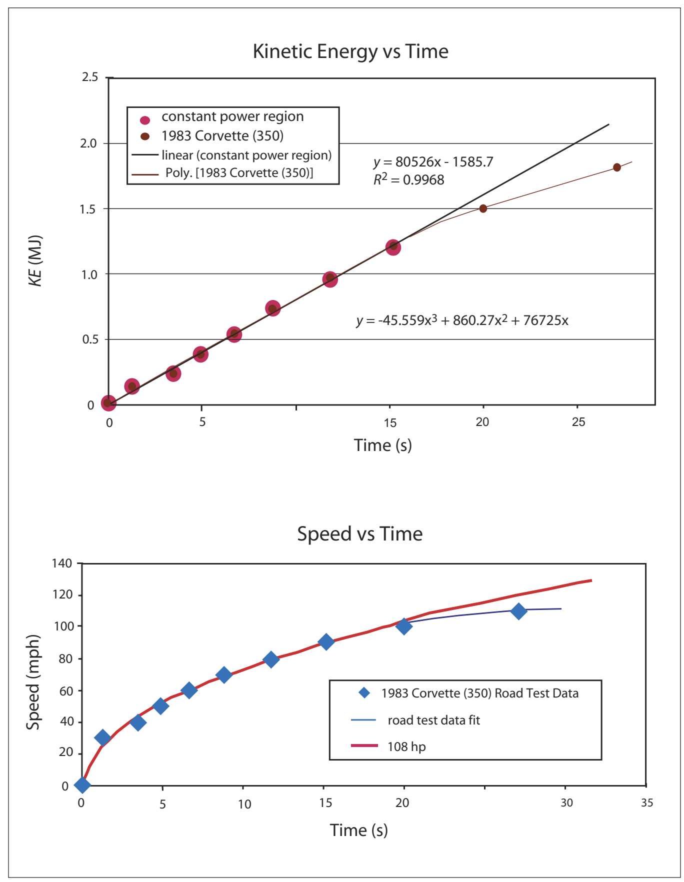

Fig. 3. Road test data from *Car & Driver*, March 1983.

the launch of the car's acceleration run and the point where its *KE* rises linearly with time. The net effect is that the car effectively loses 1.67 s off its performance numbers. Reaching 60 mph, for example, takes

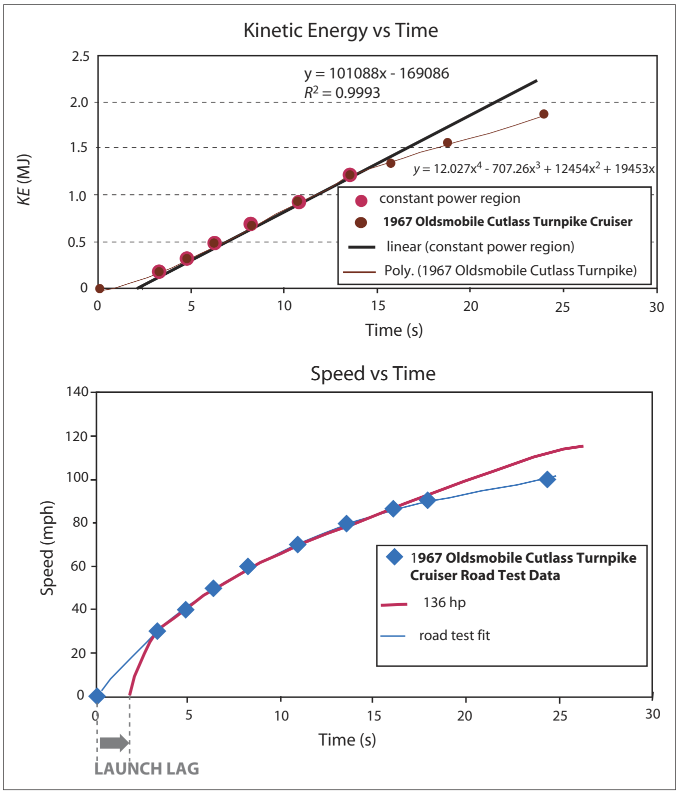

Fig. 4. Road test data from *Car Life*, April 1967.

1.67 s longer than it would have if the car's P_A were present from the moment of launch.

One reason for this 1.67 s "launch lag" is obvious to anyone who has seen a car "peel out" from a dead stop. Spinning tires generating smoke and noise often accompany hard acceleration. Power to heat tires and make a racket is not available for increasing the *KE* of the car. Even if the car is not "peeling out," similar effects in the clutch or torque converter or elsewhere can produce similar results.

Overall, the plots of *KE* versus *t* that result from automobile road tests are linear. Figure 4, which is markedly linear from 30 to 80 mph but shows both "launch lag" and "top end" effects, is typical of the more than 170 road tests of cars that the author has analyzed. He finds that with few exceptions, the *KE*-versus-*t* plot that comes from an automobile road test has a significant linear component, meaning that the available power produced by the car is largely constant.

Immediately apparent in this sort of analysis is that P_A is always substantially less than the power stated by the manufacturer. For instance, P_A for the Alpha Romeo was 48 hp. However, the power output stated by the manufacturer was 115 hp. The 1983 Corvette had a P_A of 108 hp and a manufacturer's stated power of 205 hp. Figure 4 shows the Oldsmobile had P_A = 1.01 x 10^5 J/s = 136 hp, but the manufacturer stated 300 hp.

Based on analysis of more than 170 road tests of cars ranging from the 1930s up to the present, the average automobile has a P_A that is 52% of the engine power stated by the manufacturer. Individual cars deviate significantly from this average. Some cars produce less than 35% of the manufacturer's stated power while others produce more than 70%. This yields some interesting oddities. For example, a 1964 Chrysler Imperial (340 hp stated by the manufacturer), a 1975 Corvette (165 hp stated), and a 1983 Corvette (205 hp stated), appear to have widely varying power outputs. However, all three have P_A between 105 hp and 115 hp, with the car having the lowest stated hp producing the greatest P_A and vice versa! Looking over time, these "accuracy" percentages generally improved from the mid-1950s to the early 1980s and have been fairly constant since.

There are many factors involved in why P_A is not a higher or more consistent percentage of stated power, including:

- the amount of friction in the drive train
- whether the engine produces the manufacturer's stated power over a narrow or broad range of engine speeds
- whether the drive train's gearing keeps the engine at speeds that allow it to produce near-peak power
- whether the manufacturer is being overly optimistic (to make the car appear "hot") or pessimistic (to avoid unfavorable attention from insurance, government, and consumer watchdog groups) with its power figures
- changes in standard methods of measuring engine power
- variations in individual cars

and more. One thing is for certain; the manufacturer's stated power output is not a particularly reliable indicator of what sort of power a car will have available from a performance standpoint.

Another thing that is apparent from this sort of analysis is that a car's performance in acceleration is determined by very few factors. Returning to Eq. (3) and factoring in the "launch lag" ($v_0 = 0$ at $t_0 = t_{LL}$), one gets

$$(½\, mv^2)/(t - t_{LL}) = P_A$$

or

$$t = ½\,(m/P_A)v^2 + t_{LL}\,, \qquad (5)$$

which says that the time to accelerate from zero to any speed v depends only on the "weight/power ratio" (m/P_A) of the car and the launch lag time (t_{LL}). Designing a car that can accelerate from 0–60 mph as quickly as possible means designing a car with low mass and high power, but also designing a car that can put that power into use immediately.

The 1983 Corvette, which had a very small t_{LL} of 0.03 s was tested as going 0–60 mph in 6.7 s, despite an available power of only 108 hp and a weight/power ratio of 30.6 lb/hp. A much more powerful car such as a 1971 Dodge Charger Super Bee 440, a legendary "Muscle Car" with a mammoth engine producing P_A = 174 hp and boasting a weight/power ratio of 22.7 lb/hp, would appear to be able to beat the Corvette easily. But it took 6.8 s to get from 0–60 mph, due to a t_{LL} of 1.86 s. However, in accelerating to higher speeds, where t_{LL} is less important, the Super Bee easily beats the Corvette. The Super Bee accelerates 0–100 mph in approximately 15 s. The Corvette would take almost 19 s even if it could keep its power up. In fact, the Corvette runs into "top end effects" around 90 mph and takes 20 s to go 0–100 mph.

From a teaching perspective this stuff is wonderful. Here is an interesting, challenging "real world" example of physics to which just about everyone can relate. Students often persist in the attitude that says, "That might be what it says in the book, but that's not how it works in real life." This attitude can be found even among fairly knowledgeable physics students. Analysis such as this lets students see that physics really does work and that you really can use it to learn more about even common phenomena like accelerating cars.

While the analysis presented here is fairly detailed, even more rudimentary calculations yield illuminating results. I have been giving this project to students for several years using varying degrees of depth in the assignment. Regardless of the level of detail involved, students never fail to get excited by the project—including students who do not see themselves as having a strong interest in physics and math.

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