The Rolling Wind Tunnel by Gary W. Johnson, PE, PhD January 2003

SUMMARY

A very old automotive drag measurement technique, the timed coastdown test, has been updated and improved to eliminate most of the errors from which it traditionally has suffered. The resulting test procedure produces reliable comparative data for aerodynamic drag and rolling drag, and can detect the effects of configuration changes on the order of rolling down the windows. It should be useful to the racing community for more cost-effective configuration "tuning". Implemented as a class project, it should also be a valuable teaching tool for secondary school and college students. The author has dubbed this updated technique "the rolling wind tunnel".

INTRODUCTION

<u>Coastdown Testing: the Historical Method</u>

This is a very old method, dating back to early in the 20th century, and persisting in some modern handbooks. One well-known older reference for aerodynamic drag data is that of Hoerner (**ref. 1**) who includes a chapter on the drag of land-borne vehicles. To that end, Hoerner addresses other sources of drag, principally tire rolling drag. His tire drag correlation is no longer accurate for modern radials, but has the correct functional form. The first experimental method mentioned in this chapter of Hoerner is "road tests", those being timed coastdown tests. Immediately after, he describes the difficulties encountered with wind-tunnel testing of cars, difficulties which persist to this day.

The modern Bosch Automotive Handbook (**ref. 2**), in the chapter on motor vehicle dynamics, also describes the timed coastdown method, complete with a procedure and formulas for the reader to use. This uses samples taken in the 10 mph and 45 mph speed ranges. In a world where drag coefficient is unaffected by speed and size (that is, unaffected by Reynolds number scaling), this method would work just as described, provided that one did enough repeat testing to have some confidence in the results. However, in the real world at real car sizes, speeds near 10 mph are definitely in the laminar flow range, speeds near 45 mph are definitely in the turbulent flow range, and there is most certainly a substantial difference in the measurable aerodynamic drag coefficient (Cd) for those two regimes. These effects were not well or widely known when the method was originally formulated.

The essential idea behind the coastdown method is to literally measure the velocity – time curve in a coastdown, with the car out of gear or in neutral. The time derivative of this curve is the acceleration (actually in this case deceleration) vs time curve, which by use of the velocity-time curve can be expressed as deceleration vs velocity-in-coastdown (see **Figure 1**). By Newton's third law, deceleration multiplied by mass is total decelerating force, so given a reliable weight for the vehicle during the test, the decelerating force vs velocity-in-coastdown may be obtained by this method.

The sources of decelerating force are aerodynamic drag, tire rolling drag, bearing friction, final drive friction, the effects of road slope, and the effects of wind during the test. The actual air density also plays a significant role in the value of aerodynamic drag. Of these, bearing and final drive friction are relatively insignificant, and air density can easily be determined by methods now well-known. Careful attention must be paid to the effects of slope and wind, however. Aerodynamic drag has a basic velocity-squared dependence that is complicated by large shifts of Cd with the laminar-turbulent transition. Tire drag has a dominating constant term and a small velocity-squared term, both dependent upon tire inflation and load.

Because both aerodynamic drag and tire rolling drag have a velocity-squared dependence, it is possible to analyze them easily by plotting coastdown deceleration force vs the square of coastdown speed (see **Figure 2**). In this format, the intercept is the zero-speed rolling drag, and the slope is a composite of the dominating aerodynamic Cd and the much smaller tire drag velocity-squared term. Any deviations of Cd due to Reynolds number show up as deviations from a single-slope data trend line (see **Figure 3**).

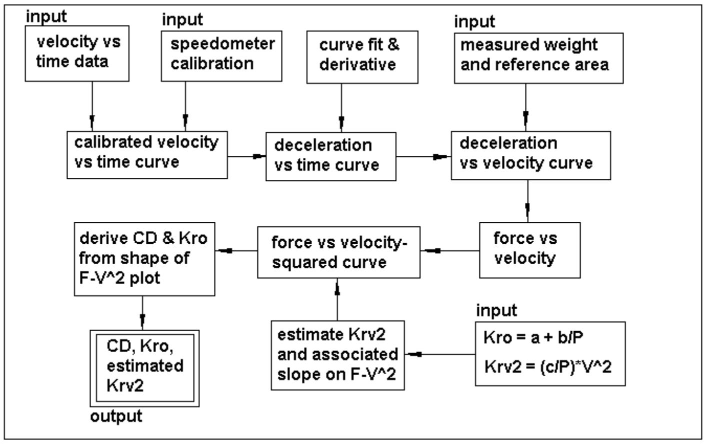


Figure 1 – Methodology for finding drag data from a timed coastdown

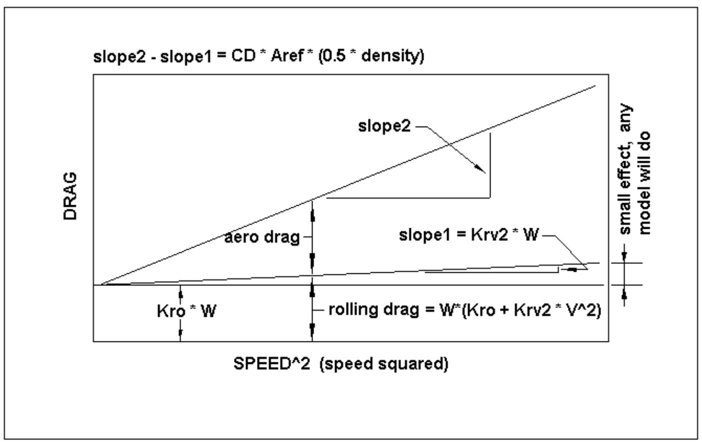


Figure 2 – Velocity-squared format provides easy way to reduce data

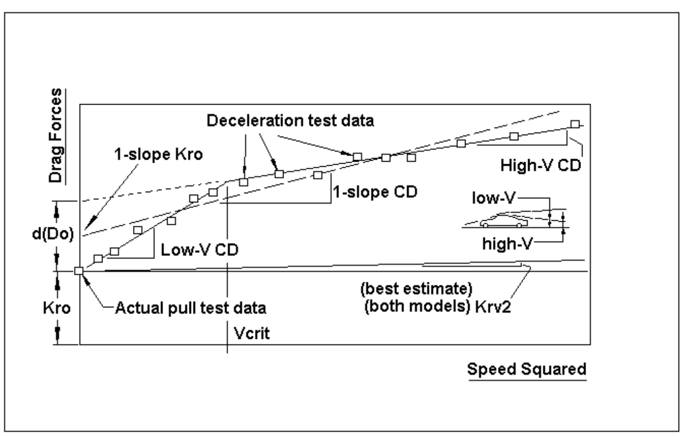


Figure 3 – Two-slope effects prevail in the “real world”

Accuracy Improvements

The procedure described in the Bosch Handbook uses simple algebraic formulas from four data points to determine two quantities: aerodynamic Cd and a constant tire drag Kr. Two points are in the high speed regime, two in the low-speed regime. No repeats or statistics are included, and there is no systematic way to incorporate actual tire drag measurements, or the effects of road slope and wind (except for averaged run times in opposite directions). The Bosch Handbook method ignores the velocity-squared term of tire drag, instead lumping that effect into aerodynamic Cd, thus constituting a slight overestimate of Cd.

A better alternative is to measure several stopwatch times as the speed decays in coastdown: thereby obtaining a smooth curve from start to finish. This can be done heading each direction along the road selected for testing, in order to "zero-out" the effects of slope and wind as much as possible, and then the entire procedure is repeated both ways to give "statistical" confidence to the results (actually, just to see if you can get the same answer twice, and if so, how close?). By measuring such a curve, the laminar-turbulent transition can be seen and allowed-for in the calculations. The tire drag velocity-squared term is small, but not insignificant. It can be estimated from theory, and then used to adjust the velocity-squared deceleration dependence. On the theory that any correction is better than none, then this theoretical correction will be close enough, since the effect is rather small.

Key to this updated coastdown technique is the actual measurement of the tire rolling drag at zero speed: in effect a driveway pull test. Any valid curve fit or modeling of drag dependence should account accurately for actual test data at zero speed. Those techniques that do not, are simply not as good, no matter how widely accepted, or widely used, they may be.

An implicit assumption in all of this is that the car's speedometer can be used to accurately measure speed during coastdown. Because aerodynamic drag and the smaller tire drag term depend upon velocity squared, a 1% error in speed measurement is a 2% error in the force measurement results. Many speedometers can be off 5 mph or more at 60 mph, about a 10% speed error (which is then over 20% on drag forces). Calibrating the speedometer is thus essential to the test. Fortunately, this is a relatively easy thing to do.

Obviously, an accurate weight is essential to success, but this is a much harder thing to do. Larger vehicles can sometimes be weighed at the local agricultural scale, although this may not be accurate enough for a 3000 to 5000 lb vehicle, because those scales may only be intended to weigh vehicles around 100,000 lb to about 1% accuracy, or the nearest 1000 lb. An error that size would clearly be disastrous for a coastdown test of a 3000 lb vehicle.

The author built a scale to weigh cars wheel-by-wheel, based on a hydraulic load cell. The wheel-by-wheel concept has the advantage of obtaining the weight distribution, and is a technique long used in aircraft weight-and-balance work. However, with four-wheeled ground vehicles, you have to shim up both wheels by exactly the same amount, at whichever end you are weighing, or the springs won't be stroked the same, and you won't get the right weight. This effect does not happen in aircraft work, because they are three-wheeled, and the spring stroke is thus unaffected by raising one wheel slightly.

To compare your results with those reported in the literature, you have to use the same reference area for your aerodynamic drag coefficient that everybody else uses for theirs. For cars, this has long been the frontal projected area, as can be seen in Hoerner, Bosch, and many other references, such as Scibor-Rylski (**ref. 3**). This can be measured quite accurately with a tape measure, and simple geometric calculations. The better job you do, the closer your results will correlate with those of others. It is customary to include the body maximum projected frontal area, and the front view of two tires, but not small protuberances like outside rear-view mirrors and antenna rods. Curves can be broken up into straight-line segments, so that everything is rectangles, triangles, and trapezoids.

Less Expensive Answers by Coastdown

Given sufficient care, with the improved coastdown method it should be possible for the average person to measure accurately the aerodynamic drag and the tire drag of a car. Doing it this way avoids the direct cost of wind tunnel measurements, which are notoriously expensive for the model and the tests. Further, testing of cars in wind tunnels suffers a variety of serious technical problems, including scaling (a Reynolds number / laminar-turbulent transition issue), and the use of a moving ground plane (a representative flow pattern issue), as described in Hoerner and many other references.

Remaining Pitfalls

The remaining pitfalls in the improved coastdown technique include road slope profile, uncertainties in car weight, and non-linearity in the speedometer calibration. Of these, road slope profile is probably the most intractable. Real-world roads don't just have a slope, they have a profile of variable slopes, almost like waves. This can be expected to impact drag test results, at the level of the small changes a person would like to see in his data, such as windows up vs windows down, roof racks, etc. To this end, all such tests intended for relative comparison must be conducted on the very same stretch of road, which must be as straight as possible (horizontally and vertically), even more so than just being generally level.

It cannot be over-emphasized that highly accurate weight is fundamental to making this method work. You simply must know the weight of the car to within 1 or 2 % to get a 1 or 2% answer on drag.

Most cars of recent manufacture will have a speedometer calibration that is easily represented with a simple correction ratio. This is necessary because the tires might not be quite the same effective diameter as they were from the factory, due to wear, or due to the substitution of an alternative make and model of tire. This type of calibration just requires that enough points be taken at one or two convenient speeds, so that one can be sure that the same answer is obtained every time.

Older vehicles might actually have some wear or corrosion in the speedometer head, so that a slope and intercept form of calibration is required. This requires more testing at speeds across the entire range, so that confidence in repeatability is high, and so that the true curve can be plotted. In extreme cases, there may be more than one slope, requiring multiple trials at a great many speeds, say every 5 mph from zero to at least highway cruising speeds. Only vehicles several decades old might exhibit this behavior.

TOOLS AND PROCEDURES

Calibrate the Speedometer

To calibrate a speedometer, one needs a stopwatch, a pencil and paper, and a piece of level road with mile markers or other landmarks separated by a precisely known distance (see **Figure 4)**. Interstate mile markers work fairly well if you use several in a row, and plot your data to expose any which might be out-of-position (as some are). Key to this is a stretch of road level enough that constant indicated speed can be maintained. If you have it, cruise control works best, of course. Record indicated speed and times-at-mile markers. You must use a stopwatch. The second sweep hand on a wristwatch is just not precise enough. Results as in **Figure 5** are a good way to reduce the data.

There is a long, straight, level bridge within a few minutes' drive of the author's house. A call to the state highway department revealed its exact length, so that this is another location that provides good calibration data for him. Each investigator must find his or her favorite test locations for this purpose.

While one is at it, calibrating the odometer is also easy. The two instruments do not necessarily share the same calibration; in fact, few do. Again, a string of interstate mile markers works quite well for this. Just be sure none are out of position. **Figure 6** shows an example data plot. There are no times to measure, unless you do this simultaneously with a speedometer calibration.

Figure 4 = Tools required to calibrate a speedometer (delete stopwatch for odometer)

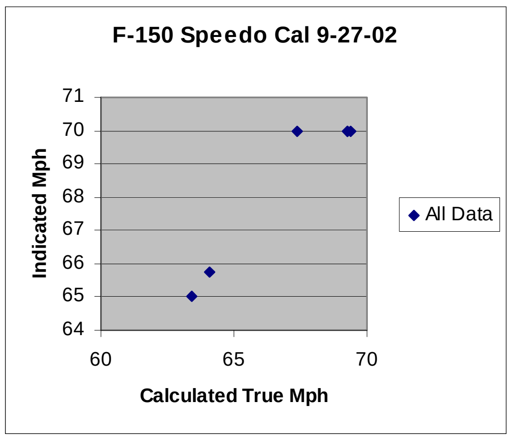


Figure 5 – A typical speedometer calibration plot (speed vs speed)

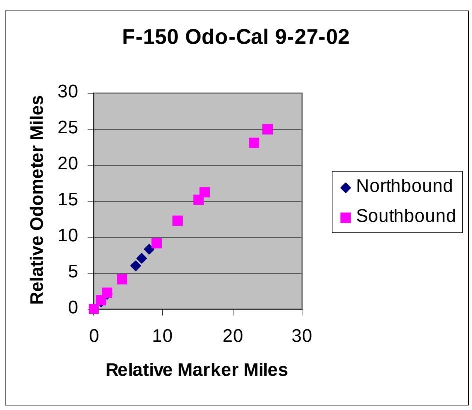


Figure 6 – A typical odometer calibration plot

Weigh the Car Very Accurately

There are three options to weigh the car. First, a commercial scale is acceptable if it has sufficient accuracy to weigh the car within about 1%. For a 3000 lb car, that is a 30 lb error. 30 lb on a scale of 100,000 lb capacity would correspond to an accuracy rating of 0.03% of full scale reading. Not many commercial scales are that good. Some are 0.1%, though. It is up to you to find out.

The second option is to buy a scale of the type used to weigh aircraft. This is a considerable expense, but might be worth it, if one were doing this for commercial purposes. The main item to consider is that the wheel at the other end of the axle has to be shimmed up by exactly the same amount as the wheel being weighed is elevated by the scale (see **Figure 7**). If this is not done, the wheel being weighed and the one diagonally opposite will stroke the springs more, and pick up extra load. The other pair will unstroke and unload. This will happen at every wheel as you weigh the car wheel-by-wheel, and thus your totaled weight results will be considerably too high.

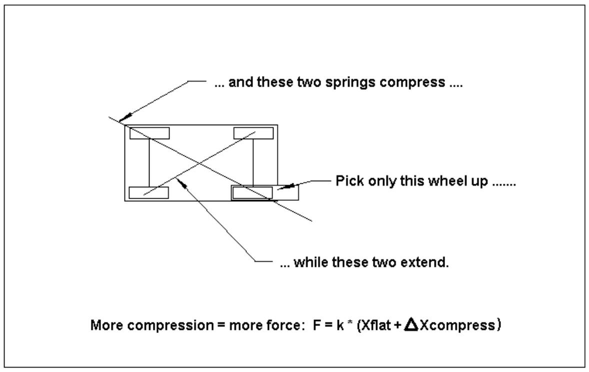


Figure 7 – Why one must shim the adjacent wheel when weighing by-the-wheel

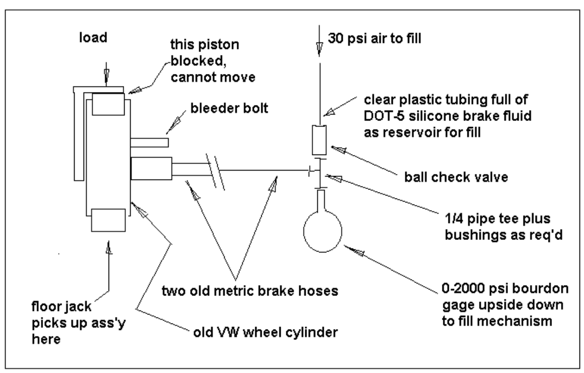


Figure 8 – How the hydraulic load cell principle is used for a scale

The advantage of weighing the car wheel-by-wheel is that you obtain directly the load distribution among the wheels, and thus center-of-gravity information in two dimensions (fore-and-aft and left-right).

The third option is to home-build your own scale. There are many principles to choose from, some easier to implement, and to de-bug of errors, than others. The author chose a "prybar scale" using a hydraulic load cell principle (**Figures 8 and 9**). This design works by picking up the wheel with a device not unlike a wheelbarrow. One raises it just clear of ground with a floor jack, against a definite fulcrum point at the other end. There is a known distance between the jack point and the fulcrum, a measurable distance between the tire contact patch and that fulcrum (see **Figure 10**), and a known pressure in the hydraulic load cell, which is actually just an old brake cylinder. This device is crude enough that it required dead-weight calibration against known weights, and it also requires repeat lifts until a consistent pressure is observed. But, it works, and it was very inexpensive to build.

Figure 9 – Prybar scale in actual use: prybar is the blue structure, hydraulics are in white lift bridge

Figure 10 – Locate tire position on scale: measure both sides of tire and average the positions

Measure the Frontal Area

One must make some measurements across the width of the vehicle (see **Figure 11**) at definite heights. The tools required to do this are simple indeed (**Figure 12**). Try to account for all the curves as best you can using a combination of rectangles, trapezoids, and triangles. See **Figure 13** for an example.

Measure the Zero-Speed Tire Drag

Measuring the zero-speed tire drag requires nothing more sophisticated than a simple spring scale from the hardware store. Most family cars and light trucks will show zero-speed drags under 55 lb on a level, smooth slab. Be sure to measure and record at what weight this data was measured, as the drag force scales directly with weight, and your coastdown test weight is likely to be different.

Figure 11 – Measuring across the vehicle as part of determining frontal area

Figure 12 – Only very simple tools are required to measure frontal area

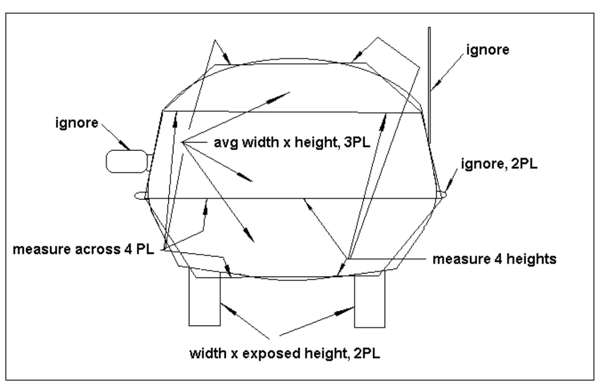
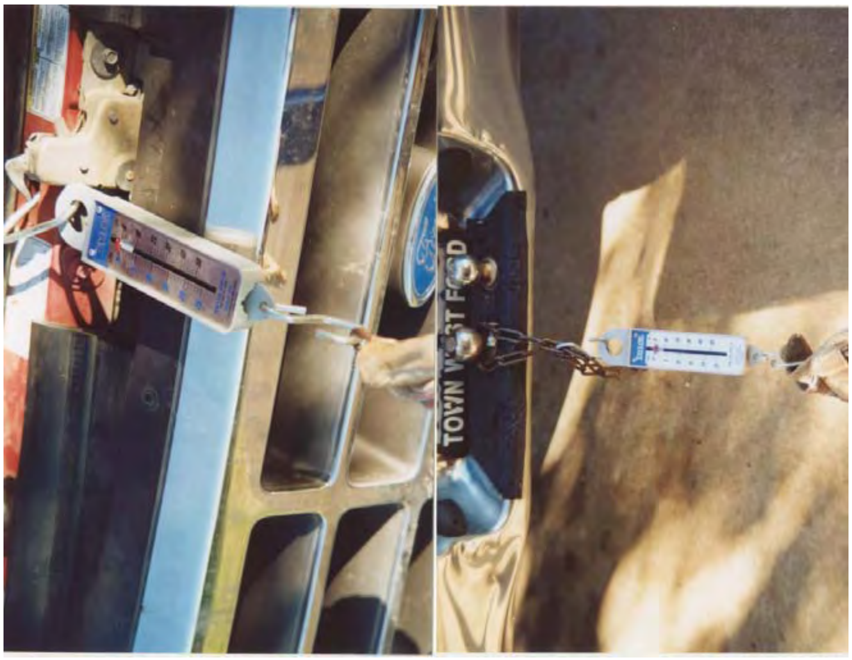


Figure 13 – Breaking an area into trapezoids, and what to ignore

You will need a smooth, level, straight driveway to make this measurement. However, no driveways are perfectly level or perfectly straight. Therefore, you will need to pull the car forward several times, then backward several times (**Figure 14**), recording the most consistent result for each direction. Then turn the car around to face the other way, and repeat the sequence of forward and backward pulls. Average the values obtained for the four combinations, and use that average as your zero-speed tire drag. The tools are nothing more than a spring scale and some hardware, pen and paper, and a calculator (**Figure 15**).



pulling forward | pulling rearward

Figure 14 – Conducting driveway pulls in both directions

Figure 15 – Tools for driveway pulls are very simple

Test Location and Conditions

You will need a stretch of straight road in an isolated place, about a half a mile long, with a place to turn around and accelerate at each end. The tools on-board include a stopwatch, pencil, and paper (see **Figure 16**). A tape recorder might help alleviate driver workload for safety's sake: sometimes it is difficult to operate the stopwatch, write results fast enough, and still drive the car. The key items here are isolation, a straight profile that is as level as possible, and decent weather (no rain, dry road). See **Figure 17**.

Figure 16 – On-board test tools for a coastdown test run

FM 2188 FM 3268

Figure 17 – Local farm-to-market roads as test sites, FM-2188 in valley, FM-3268 on a hill

It is very important that you learn the elevation of this stretch of road above sea level. A good topographic map can provide that information, or a hand-held GPS device. (The map is by far the least expensive, though.) The pressure ratio to sea level standard conditions is calculated vs altitude as P/Po = (1 – 6.88 E-06 * (altitude, feet))^5.256, a standard correlation for atmospheric pressure known for many years. See **ref. 5** for example. The temperature ratio to standard sea level conditions is (your degrees F + 459.67)/(518.67). In metric units this is (your degrees C + 273.15)/(288.15). Density ratio to standard is pressure ratio divided by temperature ratio. Standard sea level (14.696 psia, 59 F) density is 0.07651 lbm/cubic foot. Metric equivalents are 101.325 Kpa-abs, 15 C, and 1.205 kg/cubic meter. About the only thing not modeled by this technique is the effect of weather highs and lows, which truly are a secondary effect at this level of calculation. However they can be compensated by an altitude offset corresponding to the sea-level equivalent barometer offset of the high or low, using about 1 inch mercury equivalent to a 1000 feet altitude change. The standard barometer reading is 29.92 inches (760 mm) of mercury.

Conducting a Coastdown

The author finds it most convenient to do split-time measurements with the stopwatch at a series of pre-selected speeds, always starting from zero at the same initial speed. These are usually 60, 50, 40, 30, 25, 20, and 15 mph, chosen to be nice round numbers with a definite mark by which to judge the speedometer needle's movements. The change in interval at lower speeds reflects the longer time available for the driver to function as a data recorder. Typically, the author rapidly accelerates to about 65 mph, then throttles back and bumps the transmission into neutral, and starts the stopwatch as the speedometer needle hits 60 mph. He then generates split time data with the stopwatch at each speed in the list as the car coasts down. At very low speeds accuracy gets lost due to the ever-increasing relative effects of road slope profile variations. "Slick" cars will generally run out of room trying to go below 15 mph on the test sites used.

It is imperative to get more than one identical run like this, and also to get runs moving in the opposite direction over exactly the same ground. Four total runs gives one some confidence in the repeatability, and some notion of how precise that repeatability is. Two runs each in opposite directions will "zero-out" (at least to first order) the effects of wind and overall slope.

Once again, the actual test weight is critical, so record the fuel level at the start of each run, and use it to correct the weight from the fuel level of the weigh-in configuration. All occupants and equipment changes on board for the test must also be similarly accounted.

Finally, record the ambient air temperature at which the run was made. From this and the elevation of the stretch of road used as a test track, an accurate estimate of air density can be made.

After the test, you should plot your data, for both analytical and quality control purposes. The first plot is raw measured times vs measured indicated speed. You should see two curves, corresponding to the two directions, and each composed of data from two runs that should almost fall on top of each other. If your stretch of road was level enough, the two curves should not be very far apart, maybe 5-10 seconds apart, at most, at the slow end, and almost indistinguishable at the fast end. Figure the average times at each speed, plot those, and see that they fall "right in the middle". See **Figure 18**.

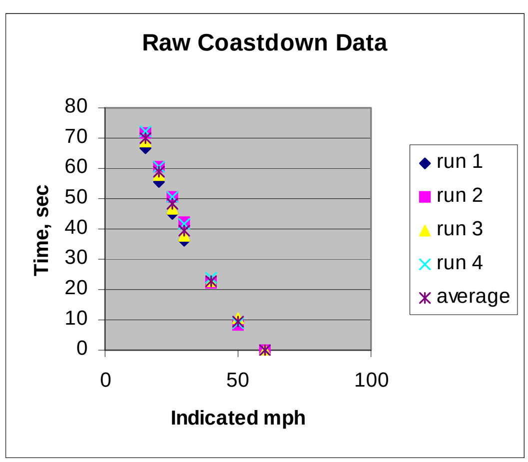


Figure 18 – Raw coastdown from F-150 / FM-3268 test as typical

Next, calibrate your indicated speed data with the speedometer calibration results, and re-plot the data as calibrated speed vs time. Do a least-squares curve fit to this plot, and add the predicted speed vs time curve, as in **Figure 19**. If you do this right, the predicted data will fall right on top of the actual average-time data. The author uses a simple third-order polynomial fit, and inverts a matrix of coefficients to find the fit constants. The method is standard, and the author obtained it from the mathematics chapter of **ref. 6** in particular. This analysis can be done very conveniently in spreadsheet software, although finding the instructions to get the software to display the entire data range of the manipulated matrices, can be an exercise in frustration.

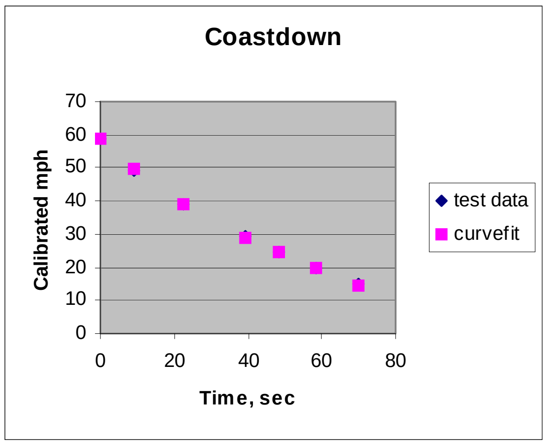


Figure 19 - Calibrated coastdown data from F-150 / FM-3268 test as typical

Any curve fit function provides an analytical form for its own derivative with time, which is the observed deceleration for this type of test. One must remember to convert from mph/second units to something that can be expressed in gees. Once the curve-fitted deceleration is expressed in gees, multiplying by the test weight for that test run provides the total observed decelerating force. This should be plotted vs the square of velocity as in **Figure20**, which is easy, because each time is already associated with a velocity. Ideally, the resulting scatter of data should look like a straight line trend in this format, because of the velocity-squared dependence of aerodynamic drag and of the smaller velocity-squared term in the rolling drag.

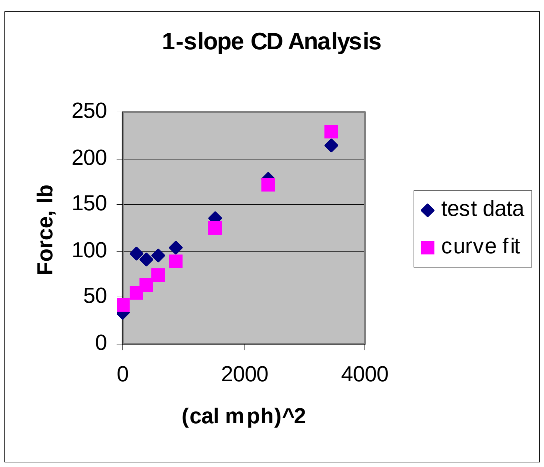


Figure 20 – Force vs velocity-squared plot for F-150 / FM-3268 test as typical, except that this plot has the zero-speed driveway pull data, and a simple one-slope linear least-squares curve fit already added to it

If the world were ideal and there were no laminar-turbulent transitions that impacted Cd, then the rest would be easy. The slope of the curve, less the slope associated with the velocity-squared term for tire drag, is directly proportional to Cd. The intercept should be the zero-speed drag, which divided by test weight, is the tire drag zero-speed coefficient Kro. However, if one adds the weight-scaled results for the driveway pulls, and fits a line to the data by least-squares, one sees that the intercept typically does not match the actual driveway pull data. Further, there are typically two slopes, or some other deviation from straight line behavior, as just seen above in **Figure 20**. Fitting a least-squares straight line to data is a simple procedure covered by a variety of sources, including **ref. 6** and **ref. 7,** which were used here.

The slope correction for the velocity-squared tire drag term is simple. It can be estimated from tire drag theory as Kr = a + b/P + (c/P)*V^2, for which pressures are measured in psig, and V in mph. This form of correlation is the same in the Bosch Handbook of today as it was for 1930's and 1940's data in Hoerner. For modern tires on modern pavements, the author uses a = -0.003, b = 0.5, and c = 8.00 E-06, derived from typical data plots presented in the Bosch Handbook. The a and b/P terms together form the zero-speed rolling drag coefficient Kro, which in turn multiplied by weight, is the zero-speed rolling drag. The c/P term, multiplied by velocity squared (in appropriate units), and by the weight, is the rolling drag increase associated with increasing velocity squared. W*c/P is therefore the increment of slope on a deceleration force vs velocity-squared plot for the tire drag velocity-squared effect.

For the old tall, narrow bias ply tires of the 1930's and 1940's, Hoerner gives values of a = 0.005, b = 0.15, and c = 35*E-06 for the rolling drag correlation constants. At appropriate inflation pressures, these typically give low-speed Kr values in the 1.3-1.5 % range. Modern radials fall around 1% even, and are well known to be "more efficient" tires, meaning lower rolling drag.

For cars that use different tire pressures front and rear, the (a + b/P) and (c/P) terms can be calculated at the appropriate pressures, and combined using the front and rear weight fractions as a weighting function. One of the real advantages of weighing the car wheel-by-wheel is that those fractions are actual measured data. For test analysis purposes, Kro = a + b/P may be adjusted to match the driveway pulls, but the velocity squared term c/P, as computed, is simply used "as is". It is a relatively small effect, so that the "any model is better than no model at all" approach is a valid approach.

To handle the slope imperfections on the force vs velocity-squared plot requires a patched two-slope solution. First, one determines where the slope break point is from a one-slope plot like **Figure 20** above. Then one uses least-squares to fit a curve to only the higher-speed range data, as in **Figure 21**. Then one fits (or tries to fit) a curve to only the low-speed range data, as in **Figure 22**. The intercept in the low-speed fit is usually quite close to the driveway-pull data, or can be made so for really anomalous low-speed behavior by repeating the driveway-pull point in the least squares analysis data set 4 or 5 times. The curve fit for the higher-speed range provides a larger intercept. The difference between the two intercepts is a value related to aerodynamic drag, and therefore density-dependent, that is required to obtain the correct levels of drag at the (usually) lower slope of this part of the data trend.

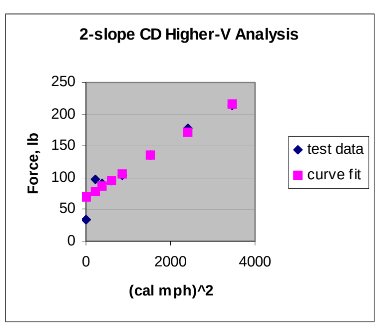


Figure 21 – Higher speed curvefit of F-150 / FM 3268 data as typical

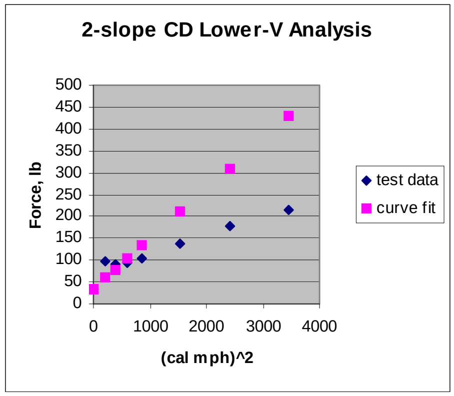


Figure 22 – "Best-attempt" low-speed curvefit for F-150 / FM-3268 data as typical; this fit passes through the driveway pull data, and through the middle of the low-end data that deviates off the high speed fit line

As most sources do not make this one- vs two-slope distinction, it is your one-slope Cd (a sort of overall average value) that should most often be compared to values reported by other investigators. However, the two-slope Cd is a better model for predictive purposes, and the high-range value so found may resemble some values reported by manufacturers that are (justifiably) proud of a low-drag design.

TESTING CONDUCTED WITH THE UPDATED METHOD

Checking the Scale Against a Known Weight

In any experiment, instruments should be calibrated against some standard, unless it is a primary standard, or something very well-known to be accurate, that you are using. Accordingly, tape measures may be presumed accurate. Thermometers may easily be checked against known data, or against standard items such as ice and boiling points. Stopwatches are usually pretty accurate, and can easily be compared to other timepieces. A weight scale is different, especially one that is home-built.

The author's home-built device depends upon three precision measurements and some known as-built dimensional data. One measurement is the pressure in the cylinder. This can be measured rather accurately with a Bourdon gage of sufficient quality. The other two measurements are the distances to the tire tread edges, from the fulcrum reference of the scale. This is done with an ordinary carpenter's square, and a tape measure. The average of the two distances is the effective distance to the center of the tire contact patch on the prybar assembly of the scale.

The (consistent) pressure measurement times the piston area in the load cell cylinder is, ideally, the force felt at the centerline of the cylinder. The mechanical advantage of this type of scale (hence the name "prybar" scale) is the ratio of distance-to-cylinder to distance-to-contact patch, all relative to the fulcrum point. The cylinder force multiplied by this ratio is the reaction at the center of the tire contact patch, provided that one has done all the error-reducing things discussed above.

The sum of such measurements for all four wheels is the vehicle weight (at the weigh-in configuration). From these data it is easy to position the center of gravity fore-and-aft, and left-to-right, using simple statics. By measuring in two dimensions where the seats, the trunk, and the fuel tank are, and recording occupant and cargo weights, and changes in fuel quantity, it is easy to correct the weigh-in result to the weight and center-of-gravity for any given coastdown test, again using simple statics. The same type of correction applies to items stored in the trunk, or elsewhere in the car, that may be different from test to test: it is simply book-keeping that must be done.

The author's experience with his home-built scale shows that the ideal cylinder force, as calculated from piston area and pressure, is simply not good enough to get an accurate weight. There is an area efficiency term that relates to the way the piston seal carries load between the piston and the cylinder walls. There is also the impact of direct static friction in the piston seal. The result is that the ideally-calculated forces are related to the actual forces by a linear curve fit. The only way to quantify this is by dead-load tests.

The author dead load-calibrated his home-made scale by placing known weights of steel stock at precisely-measured positions on the scale. The remaining uncertainties in pressure gage reading were adequately taken care of by making repeated lifts until a consistent pressure reading could be obtained. The result was a linear correlation as depicted in **Figure 23**. This particular result is unique to this scale, but the general form is not. All such devices must be calibrated in such a manner, whether hydraulic or otherwise.

After calibrating the scale, the author conducted a blind trial on a car for which the weight was independently known. In the weigh-in configuration, this 1973-vintage VW beetle should have weighed 1763 lb, as calculated and corrected from curb weight data published by the manufacturer, before the shift to the max weight-ratings data plates popular today. The author hoped to measure within 20 lb of this figure. The weigh-in result was 1765 lb. Therefore, the scale clearly worked well enough for use.

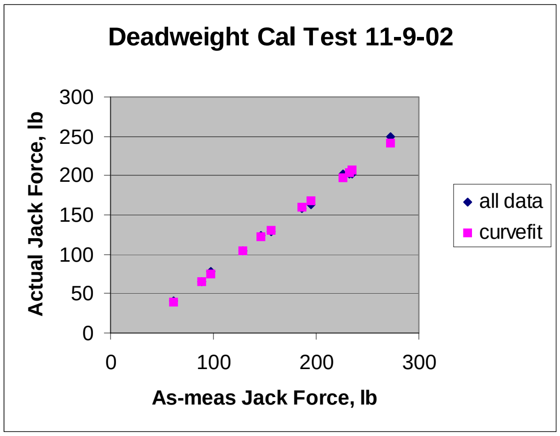


Figure 23 – Deadweight calibration data and curvefit for prybar scale

1995 Ford F-150, Tailgate Up, on FM 3268

The author's 1995 Ford F-150 XLT was weighed with this device, producing a weight near 4300 lb, which is very consistent with what one might expect for a ½-ton pickup of GVWR near 6000 lb, unloaded and unoccupied, but nearly fully-fueled. Using data obtained along Interstate 35 near Waco, Texas, the author precisely calibrated the vehicle's speedometer and odometer. The frontal area was also easily measured. Driveway pulls with the spring scale established the drag at zero speed.

The author's house is located in a rural setting. Near it is an isolated country road named FM 3268, which has a fairly straight stretch long enough to serve. Four coastdown runs (two each way) provided the data set from which the drag items were computed. **Figure 24** summarizes the one-slope and two-slope results. Based on the data reported in Hoerner and Scibor-Rylski for similar shapes, the one-slope Cd data appear quite consistent with other people's measurements. One item of note is the critical speed for transition: about 25 mph. Another is the inconsistent manner in which Cd varies in the lower speed range: a true fit there was impossible. However, this behavior is consistent with some other transition-range data reported in Hoerner, and elsewhere.

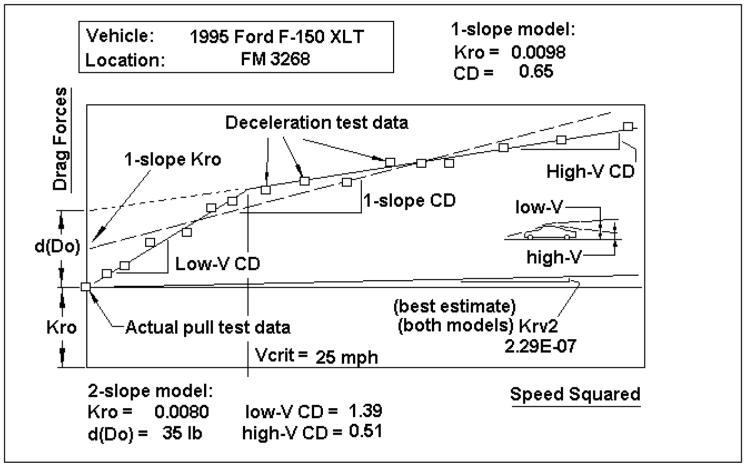


Figure 24 – Results summary for F-150 / FM-3268 test

<u>1995 Ford F-150, Tailgate Up, FM 2188</u>

Also near the author's home is a second suitable stretch of country highway along FM 2188. This stretch actually has a steeper overall slope, but a flatter slope profile (the FM 3268 site is very slightly bowl-shaped). The same test procedures were run, with results summarized in a standardized format in **Figure 25**. These results are identical in form, and slightly lower in Cd level, relative to the data obtained on FM 3268. Therefore, the method is repeatable, but it is clearly sensitive to road profile effects. Only data taken on the same test track should be directly compared. Transition speed was still about 25 mph, though.

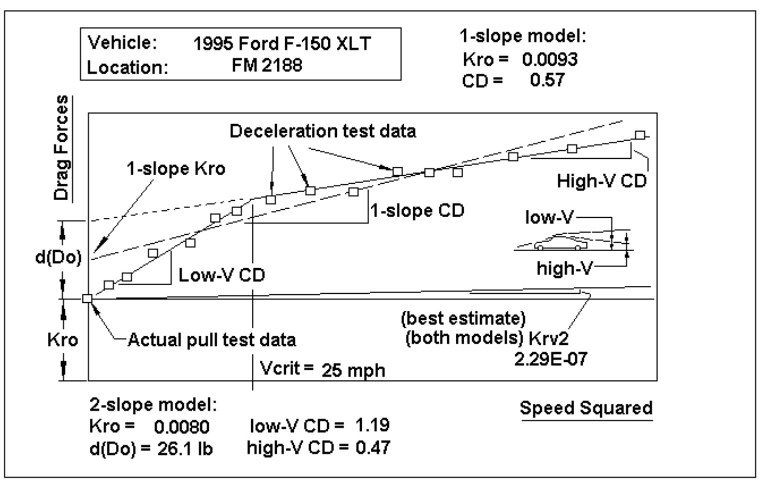


Figure 25 – Results summary for F-150 / FM-2188 test

1995 Ford F-150, Tailgate Down, FM 2188

With this in mind, the F-150 was retested on FM 2188 for the effects of having the tailgate down. The conventional wisdom is that this slightly decreases drag, thus slightly improving gas mileage. The resulting data are summarized in **Figure 26**. Comparing these to the data in **Figure 25** , we actually see a slight increase in drag with the tailgate down, as measured on the same test site. Comparing the difference to the difference between **Figures 24** and **25**, we see that the tailgate effect is smaller than the sensitivity of this test method to road slope profile differences. Transition speed was still about 25 mph.

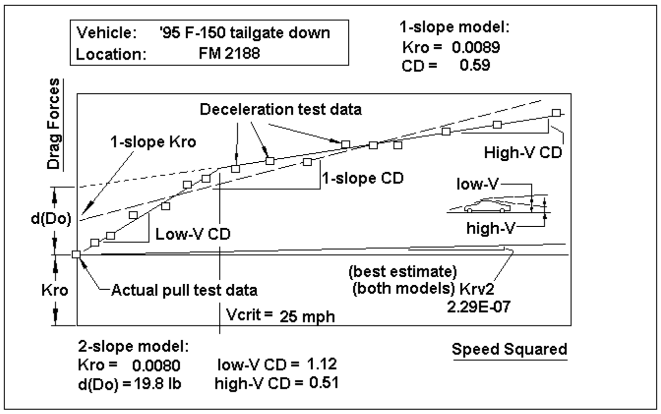


Figure 26 – Results summary for F-150 / FM-2188 test with tailgate down

1995 Ford F-150, Tailgate Up and Windows Open, FM 2188

Similarly, the author tested his F-150 with tailgate up and windows down on FM 2188 the same day he ran the tailgate-down test. Results are summarized in **Figure 27**. The conventional wisdom and logical expectations are that drag with the windows open should be higher, because of the extra momentum drag of the "scooped" air as it exchanges through the cabin. As it turns out, comparing these data with the "clean" FM 2188 test data in **Figure 25**, this time pre-conceived expectations were correct. There is indeed a slight increase in Cd, regardless of whether it is measured one-slope or two-slope. The amount of difference is comparable to the tailgate effect. Transition speed was still about 25 mph.

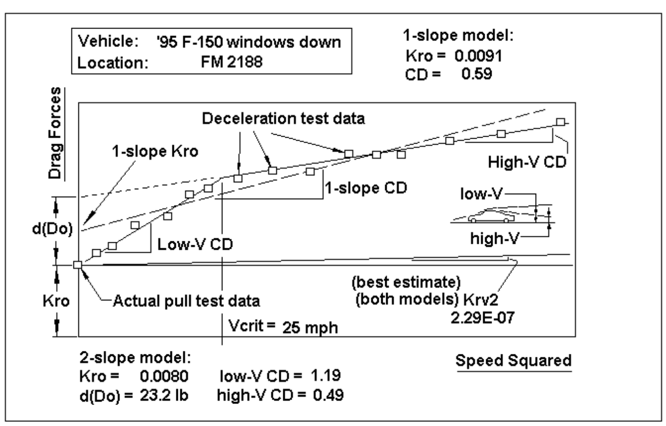


Figure 27 – Results summary for F-150 / FM-2188 test with windows down

1998 Nissan Sentra, Clean, on FM 3268

This car was tested only on FM 3268, and the results (see **Figure 28**) should only be compared directly to the other results obtained at that same site. Cd's from that site tend to run a little higher than from FM 2188. The resulting one-slope overall Cd compares quite well with data presented in Scibor-Rylski, (0.4 range). The higher-range Cd data compare very well with data reported in a recent issue of Automotive Engineering magazine (**ref. 4**) for other modern cars of similar shape, such as the Ford Focus (0.36) and the Daimler Chrysler E-class (0.26). It is even comparable to the Opel/Vauxhall Eco-Speedster concept car (0.20). The smaller Nissan seemed to have a transition speed nearer 35 mph than 25 mph.

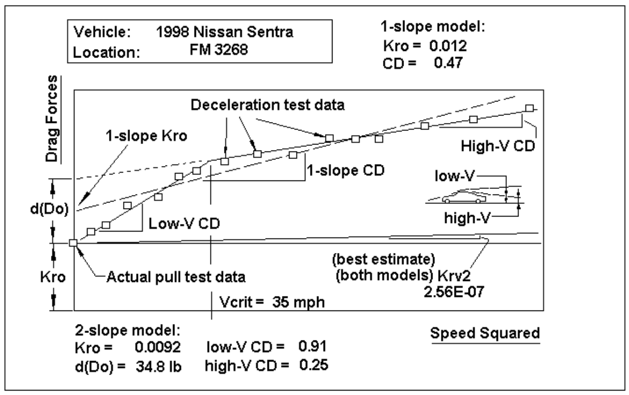


Figure 28 – Results summary for Nissan / FM-3268 test

98 Hyundai Elantra, Clean, on FM 2188

This car was tested on both sites, with a windows-down vs windows-up comparison run on FM 2188. The clean car on FM 2188 showed a similar low-speed "hook" shape to the deceleration force vs velocity-squared plot as was seen for the truck, shown earlier in **Figure 20**. The resulting one-slope and two-slope Cd's were very low, which matched the subjective impression that this car was very "clean" in terms of drag, as its body shape would suggest. Data are summarized in **Figure 29**.

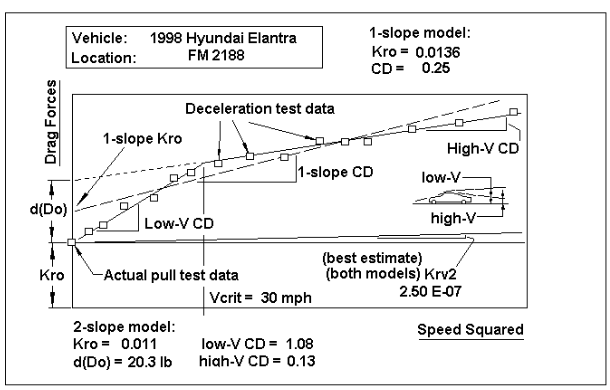


Figure 29 – Results summary for Elantra / FM-2188 test

98 Hyundai Elantra, Windows Down, FM 2188

An immediate repeat test of the Elantra on FM 2188, with the two front windows rolled down produced the drag data summarized in **Figure 30**. The overall curve shapes and behavior are substantially the same, although Cd levels are slightly higher. This is in accord with the expectations that the air exchange would increase the drag.

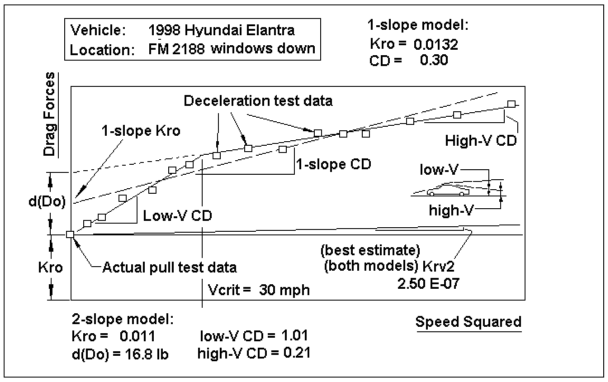


Figure 30 – Results summary for Elantra / FM-2188 test with windows down

98 Elantra, Windows Up, FM 3268

Immediately following the windows-down test, the Elantra was driven over to the FM 3268 site and tested windows-up, to provide a second-vehicle point of comparison between the two sites. During data reduction, it was noted that the transition 2-slope drag behavior was substantially different, have a slope break instead of a "hook" shape on the force vs velocity-squared plot (**Figure 31**). Note however that the same 30 mph estimate was obtained for the transition speed to the high-speed range drag regime.

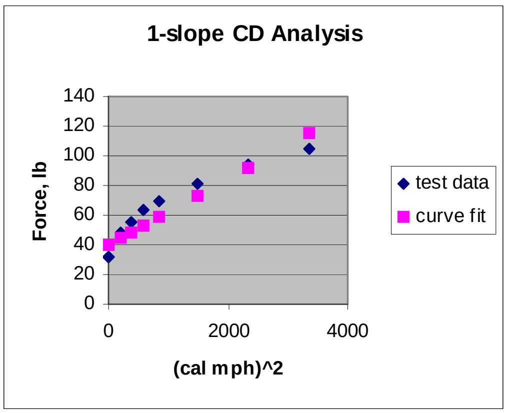


Figure 31 – Clean test of Elantra on FM-3268 did not show low-speed "hook"

Results of this test are summarized in **Figure 32**. As with the truck, drag levels are higher from the FM 3268 site than the F 2188 site. Results from this site for the Elantra, the F-150, and the two VW's can be compared directly, but there are no results for the Nissan from this site. Correspondingly, results for the

Elantra, Nissan, and F-150 obtained on FM 2188 can be compared directly, but there are no results available for the VW's from that site. The changes in drag for the F-150 and Elantra from site to site can be used to judge the probable impacts of site change on the VW's and the Nissan, however.

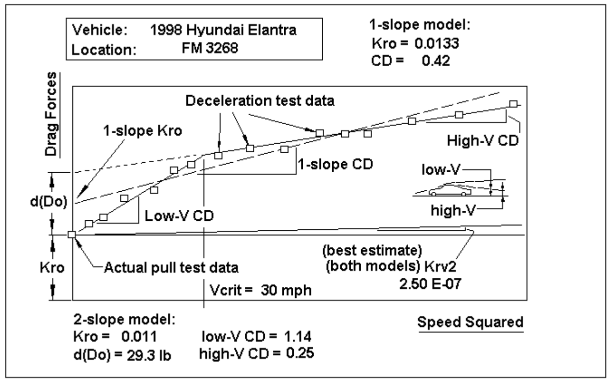


Figure 32 – Results summary for Elantra / FM-2188 test with windows up

The difference in low-speed regime Cd behavior for the Elantra between the two sites is not indicative of a failure in the basic test method. Rather, it is most likely due to a difference in the flow separation pattern induced by different wind effects at the two sites. The FM 2188 site is down in a valley, more or less protected from extremes of wind speed and turbulence. The FM 3268 site is at the top of a hill, exposed directly to extremes of wind and (especially) wind turbulence. It is well known in wind tunnel work that turbulence levels can dramatically change boundary layer flow and separation behavior.

It seems most likely that the slope-break behavior as the vehicles decelerate represents a sudden shift from the more closed-wake turbulent pattern, to the much wider-wake laminar pattern. This is similar to what is called "leading edge stall" in aircraft work, where the whole wing stalls (separates) all at once, from a start at the leading edge. The "hook" behavior in the truck and VW bus data, and the FM-2188 Elantra data, represents a gradual change across a range of speeds from the more closed-wake pattern to the wider-wake pattern. This would be analogous to what is called "trailing edge stall" in aircraft work, where the flow separation starts at the trailing edge of the wing, and gradually works its way forward to a full separation as conditions worsen.

Support for the notion of turbulence-induced sharp separation behavior on FM 3268 comes from the slope-break shapes of the data plots of the VW beetle and the Nissan, both of which are of similar size and rounded shape to the Elantra, and both of which were tested on FM 3268, where the Elantra showed the same behavior in its data.

The F-150 showed hook-shaped behavior on both sites, but it does not have a well-rounded physical shape. The VW bus was only tested on FM 3268, but showed the same hook-shaped behavior in its data. The truck and bus are actually similarly sized and shaped vehicles, lacking entirely the rounded streamlining of the passenger cars. Perhaps the effects of wind turbulence have less impact in such a case.

<u>Old Data: 73 VW Type I vs Hoerner, FM 3268</u>

Data on this vehicle had been taken a couple of years earlier on FM 3268. The original raw data set was reanalyzed by these methods, with results summarized in **Figure 33**. This is the vehicle whose published weight compared so favorably with the "prybar" scale results. Weight and drag data on this basic vehicle have been published for many years. Hoerner presents a wind tunnel-derived value of Cd = 0.37 for the beetle as it was produced ca. 1940. The 1973 model differs in some ways that would affect aerodynamic drag. These include a slightly taller and wider body, a slightly-higher ground clearance, a proportionately-larger bluff windshield, a bluffer headlight installation, a larger and bluffer bumper, and larger turn signal protuberances. The slightly-larger physical size can be taken into account with a larger frontal area. The shapes of the other factors affect drag in ways that can be estimated using the methods and data in resources such as Hoerner. Adjusting the old-beetle Cd = 0.37 for these changes, the author calculated an expected overall average Cd = 0.44, which is remarkably close to the one-slope value of 0.46 obtained in test. This smaller vehicle also seemed to have a slightly faster transition speed, near 30 mph.

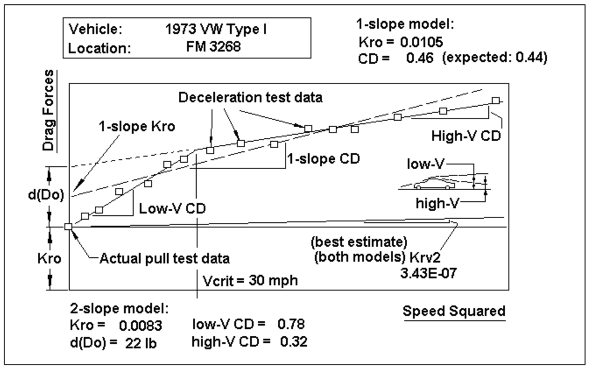


Figure 33 – Results summary for re-analyzed data on 1973 VW Type I / FM-3268

Old Data: 69 VW Type II vs Hoerner, FM 3268

The author also had some old FM 3268 data for a 1969 VW Type II Camper Bus, which could be reanalyzed to these standards. The weight for this vehicle was not readily-available published data. However, this vehicle had been weighed on an agricultural commercial scale of sufficient sensitivity to provide usable data (reportedly 0.1% of 100,000 lb full scale, or a maximum error of 100 lb). Accordingly, these data are less reliable, but still representative, until and unless a better weight figure is obtained.

This vehicle had a grossly-significant speedometer calibration ratio, but a fairly-accurate odometer. This behavior might be suspect, except that the author had personal experience with another almost-identical vehicle from the same year, with just about the same large speedometer error, and an accurate odometer. It would appear that this model was produced with a speedometer head unit that was convenient, and not necessarily accurate or “correct”, for that year at least. The message is: don’t be afraid to trust your calibrations as long as you took the pains to do them right.

This vehicle actually does have some relevant published Cd data, in Hoerner. That reference gives Cd data for two configurations, a flat-panel windshield appropriate to the early-model bus (Cd = 0.73), and a rounded-windshield configuration more like the 1969 version tested by the author (Cd = 0.43). The reanalysis results are summarized in **Figure 34**. The overall one-slope Cd is remarkably close to the rounded-windshield value from Hoerner, given the weight uncertainties. This vehicle is about the same physical size as the truck, and seemed to have a comparable transition speed: about 25 mph.

One interesting result is that the larger vehicles had the slower transition speeds, as judged from the slope-breaks in the test data. **Table 1** gives a summary of the relevant data from the tests, combined with a calculation of Reynolds number at transition, based on 30% of the vehicle’s wheelbase, which is essentially the length from the tip of the nose to about the windshield for everything but the VW bus. Values ranged from about 500,000 to about 800,000, as calculated. Interestingly enough, Hoerner and many other references show a transition Reynolds number range of 500,000 to 1,000,000 for flow along flat plates, based upon the dimension in the direction of flow.

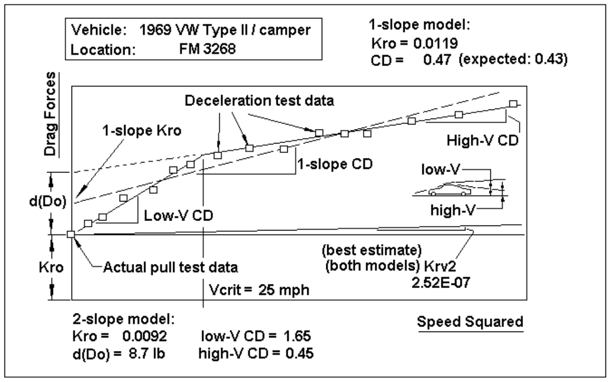


Figure 34 – Results summary for re-analyzed data on 1969 VW Type II / FM-3268

Table 1 – Transition Reynolds Number Data

vehicle	Vtrans, mph	wheelbase, in	% of length	Est. Reynolds No.
F-150	25	139	30	780,000
Nissan	35	99.5	30	820,000
VW beetle	30	94.25	30	620,000
VW bus	25	140	30	520,000
Elantra	30	100.75	30	680,000

CONCLUSIONS

The Basic Method Works

The data obtainable by these methods appears to be accurate, in that Cd's and Kro's are comparable to expectations based upon data in the literature, and laminar-turbulent transition Reynolds numbers based on 30% of the wheelbase appear to be consistent with expectations for flat plates. The method appears to be precise enough to detect the effects of configuration changes on the order of windows open or tailgate-down. The method does appear to be quite sensitive to the road slope profile of the selected test sites, so that all comparative testing should be done on the same stretch of road. (A closed runway or taxiway at an airport would be ideal, as one might expect.) Of the measurements and calibrations required to test a car this way, the measurement of vehicle weight is the most difficult and requires the greatest effort.

Using the Data for Mileage Estimates

One must make some suitable, realistic assumptions in order to use this type of data to make a fuel mileage estimate. These include the transmission power efficiency, the engine brake specific fuel consumption, and the power to drive all accessories, including oil pump and cooling, as well as electrical.

For modern automatic transmissions that feature lock up-type torque converters, 95% is not an unrealistic efficiency factor, since in lock-up mode, the slip is around 3%. For manual gearboxes, the same value is still realistic, because although there is no slip, the heavier gear lube oil is more dissipative.

Modern fuel-injected, electronically-controlled engines should operate in the vicinity of 0.40 to 0.45 BHP per lb/hr fuel flow on gasoline, which is the brake specific fuel consumption (BSFC). A much older technology such as the air-cooled VW beetle will be substantially less efficient, say BSFC = 0.50 or 0.55, much like the very similar air-cooled aircraft engines. The old VW bus that was tested had had its engine modified for extra power and mixture strength, so BSFC near 0.60 seems "reasonable" for it.

Accessory power is more of a guess, but must include the electrical, the oil pump, and the cooling water pump and fan, or a very powerful fan in the case of the air-cooled VW's. The author used guesses of 20 hp for the truck, 15 hp for the Nissan and Elantra, and 5 HP for the two VW engines.

The author had kept logbooks of maintenance and repair items and gas mileage on all but one of these vehicles. Picking off drag data at cruise speeds typical for the car, and gas mileage right out of the logbooks at those speeds, the data in **Table 2** were estimated. These data are not conclusive in any way, because one essentially assumes the values that gets the "right" answer, but it is fascinating to see how close the estimate can be with what are but "reasonable" assumptions for component efficiencies. (No data are reported for the Elantra, because no logbook-based fuel mileage values were available.)

Table 2 – Calculated Gas Mileage Based on Assumed Component Efficiencies

Vehicle	speed mph	BSFC pph/HP	trans %	accssry HP	drag lb	tot eng HP	fuel gal/hr	calcultd mile/gal	observd mile/gal
F-150	65	0.40	95	20	234	62.6	4.18	15.6	14-15
Nissan	60	0.45	95	15	106	32.9	2.47	24.3	24-27
VW beetle	60	0.55	95	5	102	22.2	2.04	29.4	28-30
VW bus	60	0.60	95	5	167	33.0	3.30	18.2	17-19

Using the Data for Racing Tests

In the racing community, regardless of type or class, it is very important to balance the drag cost vs the downlift benefit of wings and spoilers, and similar items. Further, it is difficult to know just what the local upwash or downwash directions are, so that these surfaces might be mounted for best effect. Tufts and smoke streamers can be used to help settle mounting direction questions in the field, but the only recourse most people consider for an actual lift-drag accounting is wind tunnel testing, with all the scaling difficulties and expense that type of activity entails. A less expensive option might be the "rolling wind tunnel" coastdown test technique, in which several wing or spoiler positions can be tried in rapid succession, at full scale, in a day's testing. This presents the possibility of far less expensive and potentially more accurate "tuning" of the total configuration (no moving-surface or scaling effects).

The importance of weight distributions on curved, closed race tracks is well known. The weight distribution, and the database with which to modify it, are a natural by-product of the required weigh-in for coastdown testing, if the wheel-by-wheel technique is used.

Thus the "rolling wind tunnel" seems a natural fit for more cost-effective tuning of all types of race cars.

As a Teaching Tool

Working through the physics and mathematics of this type of testing is a dramatic presentation of how to apply physics and math to something many people are already interested in: their vehicles. That makes the learning process fun for young people. In addition, working through the real-world difficulties of scale and speedometer calibration, and of handling the complicating behavior of Cd-variations with Reynolds number, are quite instructive in how to use good judgement when trying to apply theory to real life. These are very valuable lessons, whether or not the student will ever be a technically-oriented person.

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