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Using Transmission Data to Isolate Individual Losses in Coastdown Road Load Coefficients

Andrew Moskalik US Environmental Protection Agency

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Abstract

As part of the U.S. Environmental Protection Agency's (EPA's) continuing assessment of advanced light-duty automotive technologies in support of regulatory and compliance programs, the National Vehicle Fuels and Emissions Laboratory has benchmarked multiple transmissions to determine their efficiency during operation. The benchmarking included a modified "coastdown test," which measures transmission output drag as a function of speed while in neutral. The transmission drag data can be represented as a second-order expression, like that used for vehicle coastdown test results, as $F_0 + F_1V + F_2V^2$, where V is the vehicle velocity. When represented in this fashion, the relationships among the three coefficients were found to be highly predictable. The magnitude of these coefficients can be quite large, and for some tested transmissions the deviation between the quadratic regression and the measured drag at individual velocities can be significant.

To evaluate the effect of transmission losses in vehicle coastdown tests, the coastdown target and dynamometer set coefficients were pulled from the EPA's published "Data on Cars used for Testing Fuel Economy" for an entire model year. The same relationships seen among transmission coefficients were observed in the vehicle coefficients contained in these data. Therefore, the vehicle coefficients can be used directly to estimate the transmission and drivetrain losses and eliminate them from the coastdown values. With transmission losses eliminated, the remaining losses can be divided to extract more accurate estimations of aerodynamic losses and rolling losses. This process can be applied fleet-wide, using only the reported coastdown and dynamometer test coefficients to estimate the losses from individual sources. The resulting data can then be used to independently evaluate the effects of reducing each separate loss, without the need for detailed information on each vehicle in the fleet.

Introduction

The U.S. Environmental Protection Agency's National Vehicle Fuels and Emissions Laboratory (NVFEL) has benchmarked a number of light-duty engines and transmissions in support of regulatory and compliance programs. The data are used to simulate vehicle operation and losses within EPA's Advanced Light-duty Powertrain and Hybrid Analysis (ALPHA) vehicle simulation model for GHG emissions [1].

Transmission benchmark testing includes measuring torque loss over a range of input speeds and loads, as well as characterizing other losses. As part of the standard benchmarking test, the transmission output drag in neutral is recorded as a function of speed. This testing mimics transmission operation during the full vehicle coastdown testing [2], which is used to set dynamometer loads during vehicle testing. The transmission "coastdown" test data can be used to determine the proportion of the full vehicle coastdown losses that are attributable to the transmission.

This paper will start with a background on vehicle coastdown and dynamometer testing, including the representation of coastdown losses as a second-order expression and the derivation of the coefficients for this expression.

EPA's transmission testing is then described, and the neutral drag (i.e., the "coastdown" drag) test data from several individual transmissions are presented. The transmission drag is converted to a second-order expression (with appropriate coefficients), compatible with vehicle coastdown values. The trends in the transmission data are examined, and the effects on vehicle losses are discussed. The transmission data are then compared with data taken during vehicle coastdown testing, using the EPA's "Data on Cars used for Testing Fuel Economy" [3].

The transmission drag expressions show predictable trends, which are also seen in vehicle losses. These trends can be used to develop an estimate of transmission and driveline losses, using only the vehicle loss coefficients, without any additional information about individual vehicle components. A methodology to estimate transmission coastdown losses is proposed, which is furthermore used to separate the total coastdown vehicle losses into transmission, aerodynamic, and rolling resistance losses.

A large portion of this paper discusses vehicle coastdown and dynamometer testing, using the EPA's published data derived from testing of new certification vehicles [3], as well as discussing US emission and certification procedures generally. Within this context, vehicle coastdown coefficients and other characteristic values are reported in English units rather than SI units. The analysis in this paper makes substantial use of these characteristic values, and thus vehicle-related data will be presented using English units of lb-force, mph, and lb-mass preferentially, with SI units (N, kph, and kg) given for reference.

Vehicle Coastdown Testing, Dynamometer Sets, and Loss Coefficients

To certify that light-duty vehicles meet federal emissions and fuel economy standards, they are tested on a dynamometer using standard test cycles. To determine the vehicle load applied during dynamometer testing, the recommended practice is to perform a vehicle coastdown test on a track [2]. In this process, the vehicle is accelerated to a speed above 71.5 mph (115 kph), the transmission is shifted into neutral, and data are taken as the vehicle coasts down until the vehicle speed drops below 9.3 mph (15 kph). Time and speed data are collected during the coastdown and are used to determine a force-versus-speed road load expression, which is assumed to be second-order such that the total force = $F_0 + F_1V + F_2V^2$.

The main contributors to the road loads are usually classified into four groups [5, 6]:

a. aerodynamic losses, from the drag force exerted on the vehicle as it moves through the surrounding air;
b. tire rolling losses, from the resistance in the tires as the roll over the ground;
c. driveline losses, which include spin and bearing losses in the transmission and the remainder of the drivetrain;
d. minor losses, such as brake drag and wheel bearing friction, which are small compared to the other three.

Because aerodynamic losses are quadratic with speed and rolling resistance is primarily constant, it can be tempting to assign physical meaning to the three individual coefficients in the road load expression, correlating them directly with specific losses. For example, some literature assumes that the F_0 (constant) coefficient is correlated to rolling resistance, the F_2 (quadratic) coefficient to aerodynamic loads, and the F_1 (linear) coefficient to rotational losses [7, 8]. However, as demonstrated below, transmission behavior can greatly change the shape of the curves, thus simultaneously increasing and/or decreasing the values of all three coefficients. Moreover, the final coefficient values are ultimately the result of a curve fit, where the overall shape of the quadratic regression is sensitive to the effects of the transmission as well as the exact values of the data points used in the quadratic regression [9].

Vehicle Loss Coefficients

When the vehicle is transferred to a chassis dynamometer, the total road loads determined during coastdown testing must be applied during dynamometer testing. Some losses exist within the vehicle (see the red dashed box in Figure 1), but some losses need to be simulated by the dynamometer (see the purple dashed box in Figure 1). The required magnitude of the simulated loads is determined by performing a road-load derivation on the dynamometer (as in reference [4], "Chassis Dynamometer Simulation of Road Load Using Coastdown Techniques"). In this process, the simulated dynamometer losses (also a second-order force-versus-speed relationship) are "set" such that the total losses are equal to the "target" values measured during the track coastdown test.

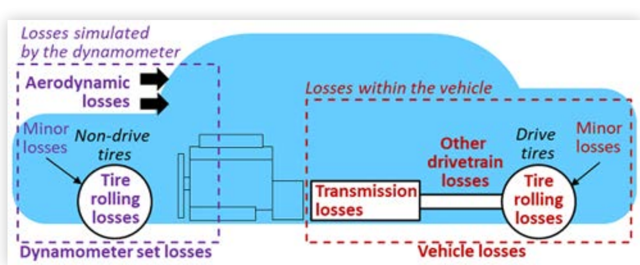
This process allows the total coastdown or target losses (designated as F in reference [4]) to be seperated into losses that need to be simulated (the dynamometer, or "dyno" set losses, designated as D) and the vehicle losses that still exist within the vehicle during dynamometer testing (designated as L). For convenience, this paper will designate constant, linear, and quadratic loss coefficients of all forces with a subscript (for example, F_0, F_1, and F_2), following the nomenclature of reference [4]. Thus, the three coefficients of the second-order expression for target losses (F_0, F_1, and F_2) can be seperated into two parts:

$$\text{Target coefficients}: F_x = L_x + D_x \left(x = 0,1,2\right) \quad (1)$$

As shown in Figure 1, the separation of the target losses into dyno set losses and vehicle losses is physically meaningful. The driveline and transmission losses, the drive tire rolling resistance, and the wheel/brake drag on the drive wheels still exist within the vehicle (see the red dashed box in Figure 1); these losses are included within the vehicle coefficients. The remaining losses - the aerodynamic drag, the non-drive tire rolling resistance, and the wheel/brake drag on the non-drive wheels - are simulated, and thus are included within the dynamometer set coefficients.

Assuming the minor brake drag and wheel bearing friction losses are relatively small (and thus can be lumped into the remaining losses), the dyno set and vehicle coefficients can each be divided into separate loss sources. Choosing T to represent transmission and drivetrain losses, A to represent aerodynamic losses, and R to represent rolling resistance (with

FIGURE 1 Losses on a two-wheel-drive chassis dynamometer. The components within the red dashed box contribute to vehicle losses; components within the purple dashed box contribute to the dynamometer set losses.



the additional subscript on R to indicate the split between dynamometer set and vehicle coefficients) gives:

$$\begin{aligned} &\text{Dyno Set Coefficients}: D_x = A_x + R_{Dx}\left(x = 0{,}1{,}2\right) \\ &\text{Vehicle Coefficients}: L_x = T_x + R_{Tx}\left(x = 0{,}1{,}2\right) \end{aligned} \quad (2)$$

See the “Nomenclature” section at the end of this paper for a full list of loss coefficient nomenclature used.

Transmissions and Vehicle Loss Coefficients

A substantial portion of the vehicle losses are associated with losses in the transmission during the coastdown; therefore, estimating transmission losses would help better define the relationships in Equation (2). However, the coastdown testing and the road-load derivation on the dynamometer are performed with the transmission in neutral. Although data on transmission losses generally are available in some cases [10, 11, 12], these data normally describe losses with the transmission in drive, and rarely or never address drag transmitted to the driveline while the transmission is in neutral.

Transmission Testing, Resulting Data, and Loss Coefficients

A number of transmissions have been benchmarked by the EPA; these were chosen to be representative of technology that is highly efficient and widely used through the fleet. Benchmarking typically focuses on transmission torque loss and efficiency, but recognizing the need for accurate modeling of all vehicle losses during coastdown, the neutral coastdown losses were also recorded for five of these transmissions.

These five transmissions represent a range of technology, including traditional automatic transmissions (ATs) and continuously variable transmissions (CVTs), as well as front-wheel-drive (FWD) and rear-wheel-drive (RWD) units. The five transmissions benchmarked by EPA were:

1. Eight-speed FWD AT from a 2018 Toyota Camry
2. FWD CVT from a 2016 Honda Civic
3. Six-speed RWD AT from a 2014 Chevrolet Silverado
4. Eight-speed RWD AT from a 2014 Ram 1500 HFE
5. FWD CVT from a 2013 Nissan Altima

Over time, the transmission benchmarking process used by the EPA has evolved, so the test location, methodology, and instrumentation for these transmission tests have changed. Rather than describe all variations of testing, this paper will, as an example, briefly describe testing of the most recent transmission, the eight-speed FWD UB80E automatic transmission from a 2018 Toyota Camry. Major differences between test processes used for the UB80E and the remaining transmissions will be noted.

Testing a 2018 Toyota Camry UB80E AT

The UB80E transmission was tested in a light duty engine dynamometer test cell, equipped with the A25A-FKS 2.5-liter four-cylinder engine from the Toyota Camry [13]. The transmission differential was locked, and the transmission output shaft was coupled to the dynamometer. Both the engine and the transmission were controlled by the stock controller. A more thorough description of the extent of this testing, as well as transmission efficiency data, is included in reference [14].

A neutral coastdown test was performed on the transmission at an approximate transmission oil temperature of 85 °C. For this testing, the engine was operated at idle, the transmission was commanded to neutral, and the engine dynamometer speed was set to 800 rpm. The dynamometer speed was then decreased to 100 rpm over 180 seconds. The torque and speed at the transmission output shaft were collected continuously, with the results shown in Figure 2.

The data shown in Figure 2 were obtained with a slow, but constant deceleration. This process is similar to that used to determine road loads during vehicle coastdown [2] or chassis dynamometer derivations [3], but is not quite identical, as no provision was made for varying the deceleration rate as would be seen in vehicle coastdown testing or preconditioning the transmission in the same way. Additionally, the losses shown in Figure 2 were measured directly rather than being calculated from the deceleration times during coastdown. However, the measured transmission losses should be representative of the transmission losses which occur during vehicle coastdown and dynamometer testing.

Determining Transmission Loss Coefficients Using Quadratic Regression

Using the CAN-based vehicle speed reported by the transmission controller, the rotational speed and torque shown in

FIGURE 2 Neutral coastdown test: Toyota Camry eight-speed AT coastdown drag torque versus speed, with a transmission oil temperature of approximately 85 °C.

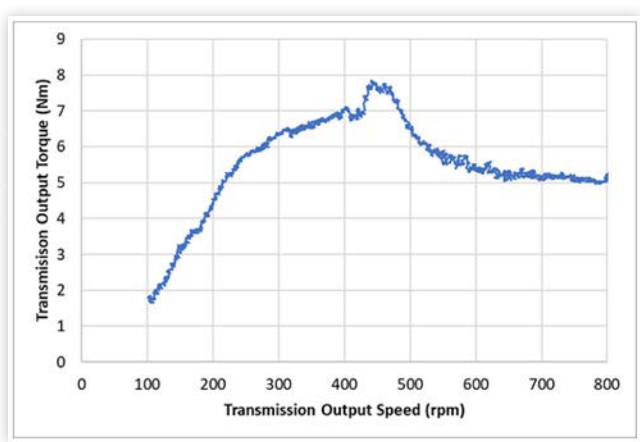


FIGURE 3 Calculated force at the wheels for a Toyota Camry eight-speed AT during coastdown.

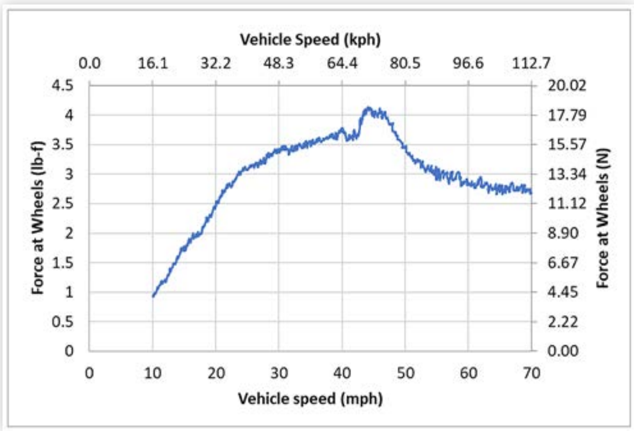


Figure 2 was converted into an equivalent vehicle speed and force at the wheels, shown in Figure 3 for the range of 10 to 70 mph (16 to 113 kph).

To determine the effect of the transmission on the vehicle coastdown drag force and the subsequent calculation of the equivalent quadratic expression, a process similar to that outlined in reference [4] for dynamometer road load derivations was used. For this process, the coastdown speeds were divided into six intervals of 10 mph (16 kph), covering a range of 10 to 70 mph (16 to 112 kph). Although reference [4] does not require these specific speed intervals, it does note that 10 mph (16 kph) intervals have been historically used for regulatory testing. The average force over each interval was calculated and applied at the midpoint speed for each interval. Finally, a quadratic regression was used to determine the second-order force-versus-speed relationship for the transmission, as shown in Figure 4.

Testing of Other Transmissions

In addition to the Toyota eight-speed AT, four other transmissions underwent coastdown drag testing. All tests extracted transmission output shaft speed and torque over a range of speeds while the engine was idling and the transmission was in neutral. However, these tests were done at different times in different labs, and thus the testing procedures, data rate, and transmission temperatures varied from transmission to transmission. Despite these variations, the final data should be reasonably representative of the actual coastdown drag associated with the transmission.

The second tested transmission was a FWD CVT from a 2016 Honda Civic with a 1.5L engine. This transmission was tested at NVFEL in substantially the same manner as the Toyota transmission, with the exception that the transmission temperature was closer to 80 °C. In addition, the maximum tested rotational speed was lower than that which corresponds to 70 mph (113 kph). To compensate, the force at 65 mph (105 kph) was estimated by extrapolating force at 55 and 45 mph (89 and 72 kph). The resulting calculated drag force at the wheels and equivalent quadratic expression are shown in Figure 5.

The third transmission, also tested at NVFEL, was a RWD 6L80 longitudinal six-speed AT from a 2014 Chevrolet Silverado with a 4.3L engine [15]. For this testing, the average transmission temperature was 78 °C. The resulting calculated drag force at the wheels and equivalent quadratic expression are shown in Figure 6.

The final two transmissions were tested at FEV's North American Technical Center, under contract from the EPA. These two transmissions were a RWD 845RE transmission from a 2014 Ram 1500 HFE with a 3.6L engine [16] and a FWD Jatco CVT8 from a 2013 Nissan Altima with a 2.5L engine [17]. For both transmissions, the data were collected at multiple temperatures, and collected as a series of steady-state tests at various speeds rather than as a continuous

FIGURE 4 Calculated vehicle speed and force at the wheels for a 2018 Toyota Camry eight-speed AT during coastdown, with the equivalent quadratic expression. The transmission temperature was approximately 85 °C during testing.

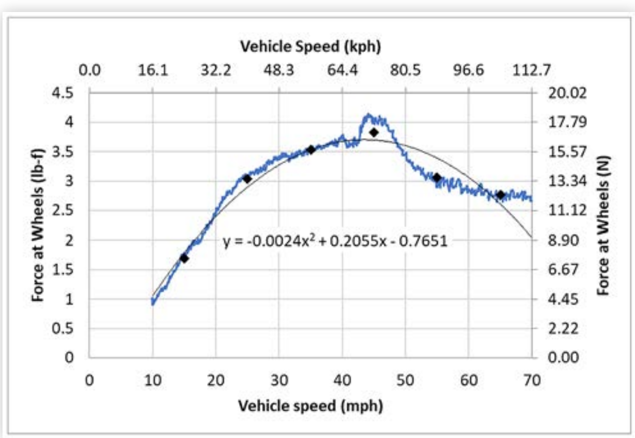


FIGURE 5 Calculated vehicle speed and force at the wheels for a 2016 Honda CVT during coastdown, with the equivalent quadratic expression. The transmission temperature was approximately 80 °C during testing.

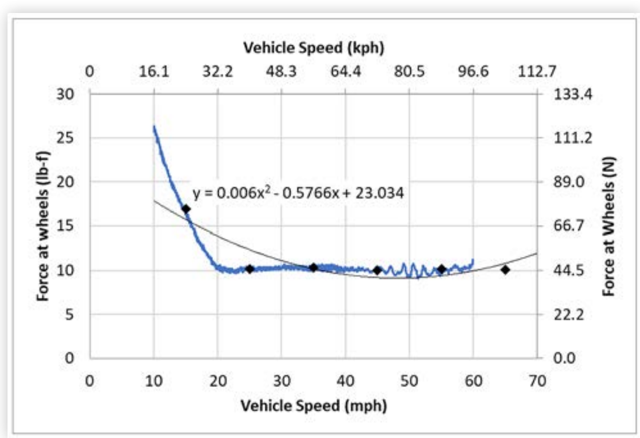


FIGURE 6 Calculated vehicle speed and force at the wheels for a 2014 Chevrolet Silverado six-speed AT during coastdown, with the equivalent quadratic expression. The transmission temperature was approximately 78 °C during testing.

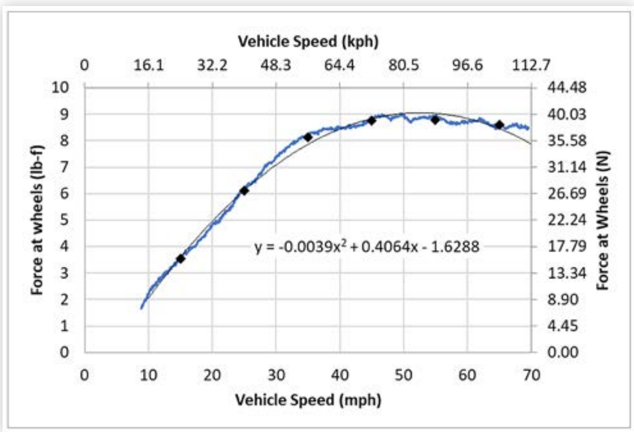
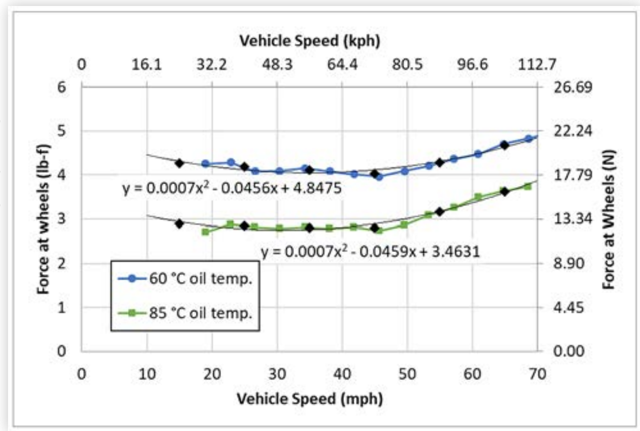


FIGURE 8 Calculated vehicle speed and force at the wheels for a 2013 Nissan Altima CVT during coastdown, with the equivalent quadratic expression. The transmission temperature varied during testing as shown.



deceleration. The six midpoint force values were interpolated from the available data as required. For the Nissan, the force at 15 mph (24 kph) was extrapolated from the available data similar to the Honda extrapolation discussed above. The calculated drag force at the wheels and equivalent quadratic expression for the two transmissions are shown in Figures 7 and 8.

Differences and Similarities among the Transmissions

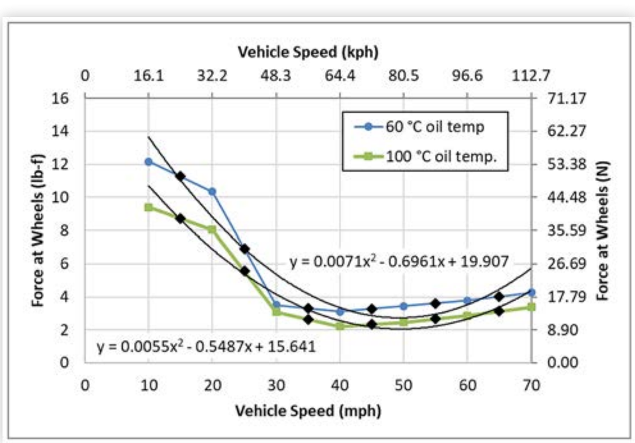
The data shown in Figures 4 through 8 exhibit some interesting contrasts among the tested transmissions. For example, the two RWD transmissions from trucks (the Silverado in Figure 6 and Ram in Figure 7) exhibit starkly different trends, with the Silverado transmission drag increasing with speed through the lower speeds, while the Ram transmission drag decreases with speed, resulting in substantially different curve shapes between the two.

Also interesting is the clear operational bifurcation in some of the transmissions, notably the Toyota in Figure 4 and the Honda in Figure 5 (and, to some extent, the Ram in Figure 7). This bifurcation results in drag that is piecewise smooth and predictable, but is less well-approximated by the quadratic regression assumed for coastdown testing. The quadratic estimation for the Honda, for example, differs from the measured data by around four pounds (18 N) at 20 mph (32 kph) and eight pounds (36 N) at 10 mph (16 kph).

These bifurcations are likely caused by active operation of the transmission during the coastdown. For example, the Honda CVT (Figure 5) increases clamping pressure at lower speeds, and the Ram transmission (Figure 7) actively engages different shift elements during deceleration.

As a result of the operational bifurcations, losses in some transmissions are not necessarily well-approximated by a second-order function. This is potentially significant as, in current practice, the target losses from the vehicle coastdown and the dynamometer set losses are both established using a second-order function [2, 4].

FIGURE 7 Calculated vehicle speed and force at the wheels for a 2014 Ram 1500 eight-speed AT during coastdown, with the equivalent quadratic expression. The transmission temperature varied during testing as shown.



Comparison of All Transmission Coastdown Parameters

The calculated coefficients for the equivalent quadratic expressions from all the tested transmissions are collected in Table 1, where the total force at the vehicle wheels due to transmission drag is equal to $T_0 + T_1V + T_2V^2$.

TABLE 1 Transmission coefficients, where the total force = $T_0 + T_1V + T_2V^2$. Coefficients are given in both English and SI units. The label (second column) is used to identify points in Figures 9 and 10.

Vehicle	Label	Trans	Appx Temp °C	T_0 lbs. (N)	T_1 lbs/mph (N/kph)	T_2 lbs/mph² (N/kph²)
2018 Toyota Camry	T	AT8	85	-0.765 (-3.40)	0.206 (0.568)	-0.00236 (-0.00405)
2016 Honda Civic	H	CVT	80	23.03 (102.44)	-0.577 (-1.594)	0.00597 (0.01026)
2016 Chevrolet Silverado	C	AT6	78	-1.629 (-7.25)	0.406 (1.124)	-0.00387 (-0.00664)
2014 Ram 1500 HFE	R	AT8	60	19.91 (88.56)	-0.696 (-1.924)	0.00705 (0.01212)
			100	15.64 (69.6)	-0.549 (-1.517)	0.00555 (0.00953)
2013 Nissan Altima	N	CVT	60	4.85 (21.57)	-0.046 (-0.126)	0.00065 (0.00112)
			85	3.463 (15.40)	-0.046 (-0.127)	0.00074 (0.00127)

FIGURE 9 Linear (T_1) and quadratic (T_2) transmission coefficients for the five tested transmissions, with a linear regression fit through the data. The labeling letter indicates the specific transmission, as given in Table 1.

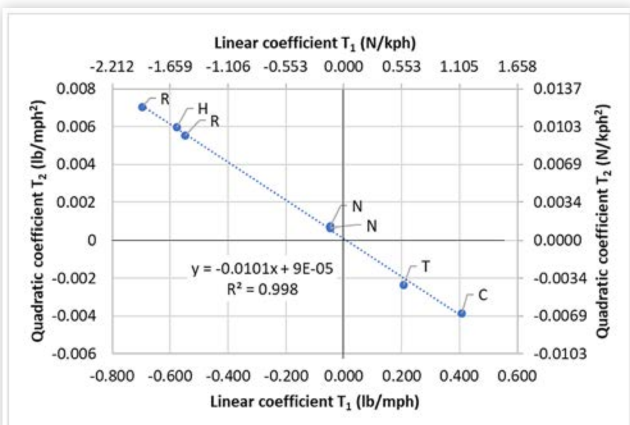
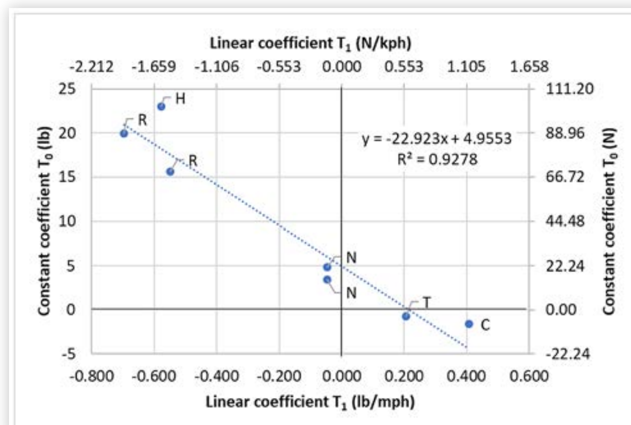


FIGURE 10 Linear (T_1) and constant (T_0) transmission coefficients for the five tested transmissions, with a linear regression fit through the data. The labeling letter indicates the specific transmission, as given in Table 1.



The transmissions tested represent a wide range of vehicles and transmissions: trucks and cars, automatic transmissions and CVTs, rear-wheel and front-wheel drive units. However, the resulting quadratic coefficients are predictably related. Figure 9 shows the relationship between the linear (T_1) and quadratic (T_2) coefficients for these five transmissions.

For this range of transmissions, the two coefficients are nearly perfectly linearly related, with $T_2 = -0.0101T_1$ (or, more easily, $T_2 = -T_1 / 99$) in English units. Although not as perfectly aligned, the constant (T_0) and linear (T_1) coefficients also have a predictable relationship, as shown in Figure 10. The best-fit linear regression is also shown.

For the two transmissions which were tested at different temperatures, there was some change in the magnitude of the coefficients with temperature - particularly for the Ram - but very little change in the relationships among the coefficients (see Figures 9 and 10). Since adjusting the data for temperature had little effect on the final expression for the relationships between coefficients, all tests were used. With this information, the constant (T_0) and quadratic (T_2) coefficients for a transmission system can be estimated from the linear coefficient (T_1) using the following two relationships:

$$\begin{aligned} T_2 &= -T_1/99 \quad T_0 = -22.9 \quad T_1 + 5.0 \ (\text{English}) \\ T_2 &= -T_1/159 \quad T_0 = -36.9 \quad T_1 + 22.2 \ (\text{SI}) \end{aligned} \tag{3}$$

Examining Vehicle Loss Coefficients in Sample Vehicles

Transmission losses make up a portion of the vehicle losses, and the trends seen in the relationships among transmission coefficients (Equation 3) should influence the relationships seen among vehicle coefficients. To examine the extent of this influence, for each of the five tested transmissions, vehicles of the same model year were identified within the published test data [3] which contained the same engine and the same tested reference transmission. For each vehicle, the target coefficients (F_0, F_1, and F_2) and dyno set coefficients (D_0, D_1, and D_2) were extracted, and the difference calculated (Equation 1) to obtain the vehicle loss coefficients (L_0, L_1, and L_2).

The vehicle loss coefficients for the group of vehicles containing the tested transmissions are shown in Figure 11 and Figure 12, along with the transmission coefficients calculated above. Vehicles and transmissions are identified in these figures by manufacturer (Honda, FCA, Nissan, Toyota, and GM).

As expected, Figures 11 and 12 show vehicle losses which are higher than losses in the transmission alone. The vehicle loss coefficients not only contain losses associated with the

FIGURE 11 Linear and quadratic vehicle coefficients (L_1 and L_2) compared with the transmission coefficients (T_1 and T_2) and the regression lines fit through the transmission data from Figure 9.

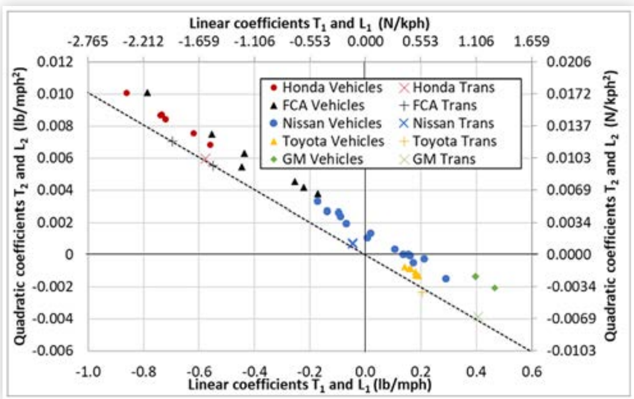
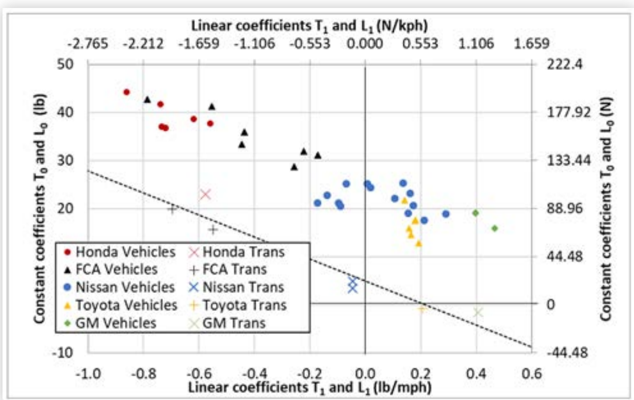


FIGURE 12 Linear and constant vehicle coefficients (L_1 and L_0) compared with the transmission coefficients (T_1 and T_0) and the regression lines fit through the transmission data from Figure 10.



transmission, but also contain tire rolling losses and some additional brake or bearing drag.

These additional losses - i.e., the distance "above" the regression lines shown in Figures 11 and 12 - very roughly increase with the mass of the vehicle. For example, the heaviest vehicles in the sample are the GM vehicles, identified in green in Figures 11 and 12. These vehicles are around 0.0005 lb/mph^2 (0.00086 N/kph^2) "higher" above the line in Figure 11 than the next heaviest vehicles (most of the FCA vehicles), and at approximately the same height "above" the line in Figure 12.

Examining Vehicle Loss Coefficients in the Entire Model Year 2019 Fleet

The results from this group of vehicles imply that vehicle loss coefficients can be predictable, but this inference was based on only vehicles containing five specific transmissions. To see if these relationships can be generalized, vehicle loss coefficients were calculated for all vehicles from model year 2019 (MY 2019), using the target and dyno set coefficients from EPA's published test data [3]. The fleet data set contains a wider variety of transmission types than the five benchmarked by the EPA, including manual transmissions (MTs) and dual clutch-transmissions (DCTs) in addition to ATs and CVTs, four-wheel drive (4WD) and all-wheel drive (AWD) units in addition to FWD and RWD, and both hybrid vehicles and battery electric vehicles (BEVs).

The resulting data were condensed by eliminating duplicated vehicle loss coefficients (i.e., tests using the same dynamometer road load derivation). After removing duplicates, data outliers were removed; these were substantially vehicles whose dyno set coefficients were either clearly incorrect (of the wrong magnitude, identical to the target coefficients, or identical to other vehicles with different target coefficients) or were still equal to the default estimated coefficients (as given by the default estimate calculations in reference [4]).

The remaining data set contained 1169 different vehicle tests. Significantly, the data set includes both BEVs and hybrids, which have distinctively different "transmissions," as well as vehicles with traditional ATs, CVTs, and MTs. The vehicle loss coefficients are shown graphed against each other in Figures 13 and 14. Both figures also show the trend lines from Figures 11 and 12, as well as the average coefficient values (in orange). The data presented in these figures are for individual tests and are not weighted by sales or other metrics. Thus, the average values shown by the orange dots are useful for visual orientation within the figures but are not necessarily reflective of actual sales-weighted fleet averages.

Distribution of Vehicle Loss Coefficients: Automatic Versus Manual Transmissions

As shown in Figure 13, both the linear and quadratic vehicle loss coefficients cover a wide range. In particular, the linear

FIGURE 13 Linear and quadratic vehicle coefficients (L_1 and L_2), for MY 2019 vehicles. The orange dot indicates the average values; the dashed line is the trend from Figure 11.

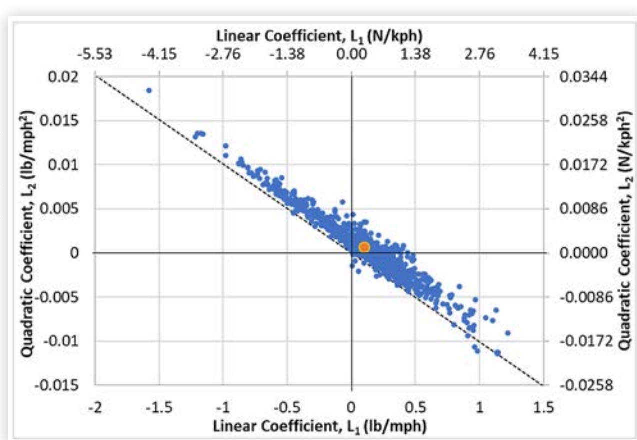


FIGURE 14 Linear and constant vehicle coefficients (L_1 and L_0), for MY 2019 vehicles. The orange dot indicates the average values; the dashed line is the trend from Figure 12.

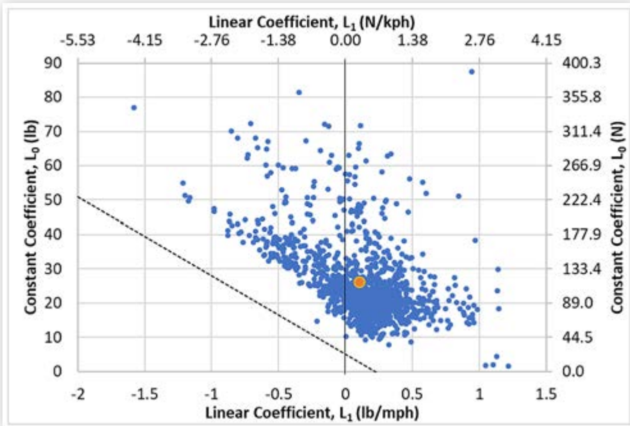
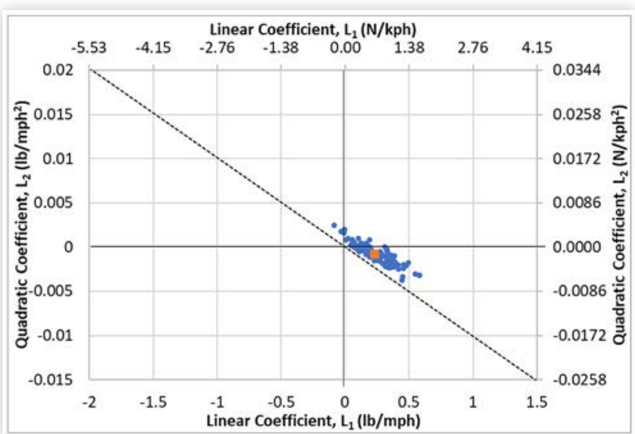


FIGURE 15 Linear and quadratic vehicle coefficients (L_1 and L_2) for all MY 2019 vehicles with manual transmissions. The orange dot indicates the average values; the dashed line is the trend from Figure 11.

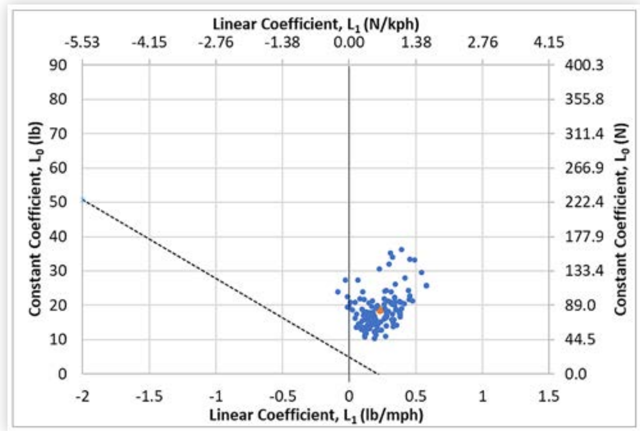


vehicle coefficient generally spans values from -1.0 to +1.0 lb/mph (-2.76 to +2.76 N/kph), with around 85% of the values located between -0.5 to +0.5 lb/mph (-1.38 to +1.38 N/kph).

A potential reason for the wide span of vehicle loss coefficients is the active control of automatic transmissions, which changes the shape of the loss curve as seen in the transmission drag data above. To contrast, all manual transmission vehicles were extracted from the MY 2019 data set. These vehicles include a wide array of transmissions of different torque capacities, both FWD and RWD, from different manufacturers. The resulting vehicle loss coefficients, representing 148 tests (about 12.5% of the total) are shown graphed against each other in Figures 15 and 16.

These figures show that for transmissions which do not have automatically controlled elements, the coefficients are grouped much more tightly. Thus, the differences among

FIGURE 16 Linear and constant vehicle coefficients (L_1 and L_0) for all MY 2019 vehicles with manual transmissions. The orange dot indicates the average values; the dashed line is the trend from Figure 12.



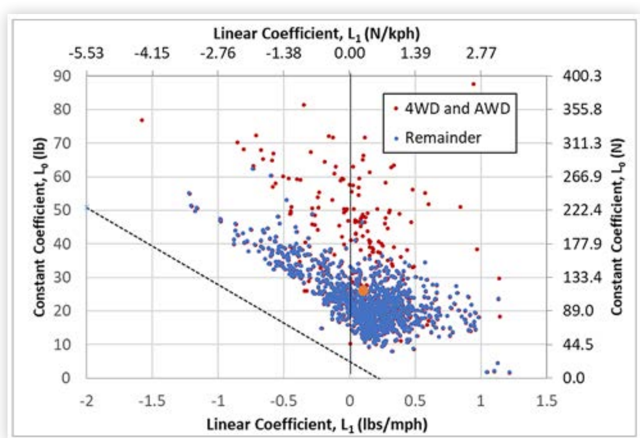
transmissions may not be generally due to architecture, but more due to control schemes, with transmissions actively changing their internal drag during coastdown and thus changing the magnitudes of the vehicle loss coefficients.

The Effect of Two- and Four-Wheel Drive Dynamometers

Figure 14 shows a sparse but significant group of vehicles with much high L_0 values than the average. These are primarily vehicles which have been flagged as 4WD or AWD in the data source [3]. Figure 17 shows the same data, with the vehicles designated as 4WD and AWD indicated in red.

The majority of these vehicles appear to have been tested on a four-wheel drive dynamometer, where the vehicle losses include rolling resistance from both axles rather than only a single axle.

FIGURE 17 Linear and constant vehicle coefficients (L_1 and L_2) for MY 2019 vehicles. 4WD and AWD vehicles are indicated in red.



Separation of Loss Coefficients Into Component Causes

The relationships among transmission coefficients can be used to separate out an estimated transmission/drivetrain loss from the vehicle road load coefficients, making it easier to estimate the remaining losses included in the target coefficients. To aid in this process, some simple assumptions on the form and magnitude of the various losses are made:

a. Aerodynamic losses are assumed to be purely quadratic with vehicle speed, as in the standard expression where force = ½($\rho C_d A$)V^2 [2].
b. Tire rolling resistance is assumed to have both linear and constant components. Although the form and magnitude of the effect is not well established, rolling resistance does generally change with vehicle speed [18, 19, 20, 21], and the assumption of a linear form is a reasonable approximation.
c. The remaining losses - brake and hub drag, for example - are assumed to be relatively small, and are lumped into the tire rolling resistance.

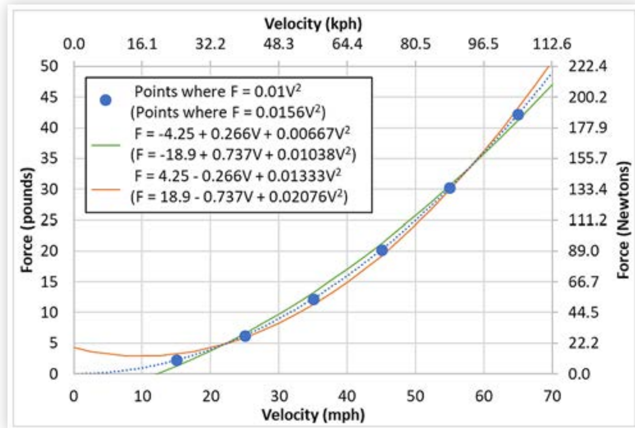
From Equation (2), transmission losses are entirely contained in the vehicle loss coefficients, L_x, while aerodynamic losses are entirely contained within the dyno set coefficients, D_x, and rolling resistance losses are assumed to be split between the two.

Based on the assumption that aerodynamic losses are purely quadratic, it is tempting to simply assume the quadratic dyno set coefficients represent the aerodynamic losses and allocate the remaining coefficients to the appropriate losses. However, the coefficient values are not individually linked to specific losses; they are the result of a curve fit to experimental test data. Small shifts in measured values due to test-to-test variation can alter the balance of the final coefficients without substantially affecting the calculated losses at any one speed.

As an example, Figure 18 shows six data points in blue lying along the purely quadratic curve of $F(lbs) = 0.01V^2$ [$F(N) = 0.0156V^2$ in SI units]. The six data points are located at velocities of 15 mph (24 kph), 25 mph (40 kph), and so on, consistent with the midpoints of the speed intervals historically used for regulatory testing as outlined in reference [4]. The other two quadratic curves shown (in green and orange) both deviate from the data points by no more than ±1 pound (±4.45 N), yet the coefficients are significantly different, with the constant coefficient ranging ±4.25 pounds (±18.9 N) and the quadratic coefficient changing by a factor of two.

To avoid over-relying on the exact values of the coefficients measured during any specific vehicle test, the following analysis will develop an additional relationship between the rolling resistance coefficients, using the fleet test data. It will also develop relationships among aerodynamic loss coefficients to create a pure quadratic estimation of the aerodynamic drag.

FIGURE 18 Quadratic fit of data points. The six blue data points are on the purely quadratic curve in blue. The other two curves shown are within ±1 pound (±4.45 N) of the six data points. Equations are given in both English and SI units.



Rolling Resistance

To begin a calculation of tire rolling resistance, an estimate of the transmission losses was removed from the vehicle loss coefficients. Assuming the quadratic vehicle loss coefficient (L_2) is entirely due to the transmission, the relationships from Equation (3) can be applied to give an estimate of the other transmission coefficients.

$$\begin{aligned} &T_2 = L_2;\ T_1 = -T_2 \times 99;\ \ T_0 = -22.9\,T_1 + 5.0\ \ (\text{English}) \\ &T_2 = L_2;\ T_1 = -T_2 \times 159;\ T_0 = -36.9\,T_1 + 22.2\ \ (\text{SI}) \end{aligned} \tag{4}$$

These can then be subtracted from the vehicle loss coefficients, leaving a constant and a linear term to represent the rolling resistance (which include primarily tire losses, along with a component of brake drag and other minor losses).

The two remaining vehicle coefficients, constant and linear, are shown in Figure 19 for all MY 2019 vehicles. The scattering of vehicles having high values for both coefficients are for the most part flagged as 4WD and AWD and are likely tested on four-wheel drive dynamometers.

In Figure 19, the averages of the coefficients are 23.5 lbs (104.5 N) and 0.165 lbs/mph (0.455 N/kph), which represents an increase in rolling resistance of about 30% between 15 mph and 65 mph (24 kph and 105 kph). Although the average losses represented here certainly include losses from sources other than tires (brake drag, for example), the ~30% increase over the given speed range is within the range of examples given in the literature for tire rolling resistance [18 - 21].

The portion of losses arising from tire rolling resistance specifically (and to some extent the remaining minor losses) should be proportional to vehicle weight. As a check, the AWD and 4WD vehicles were temporarily removed from the data set, and the remaining vehicle coefficients were compared to the equivalent test weight (ETW), with results shown in Figure 20.

Although there is considerable scatter, as would be expected from a large group of vehicles with variations in

FIGURE 19 The remaining vehicle constant (L_0 - T_0) and linear coefficients (L_1 - T_1) for all vehicles; red dots indicate 4WD and AWD flagged vehicles. The orange dot represents the average values.

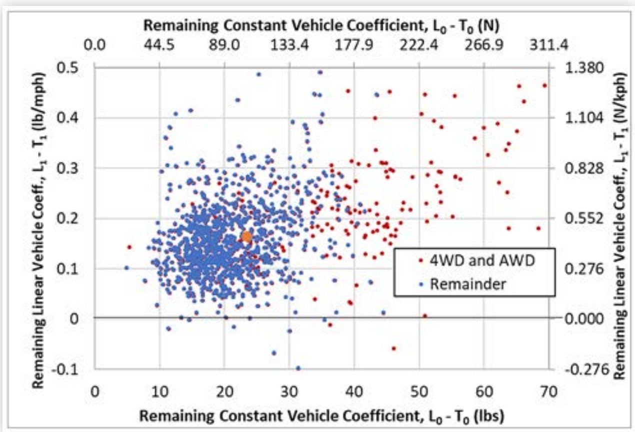
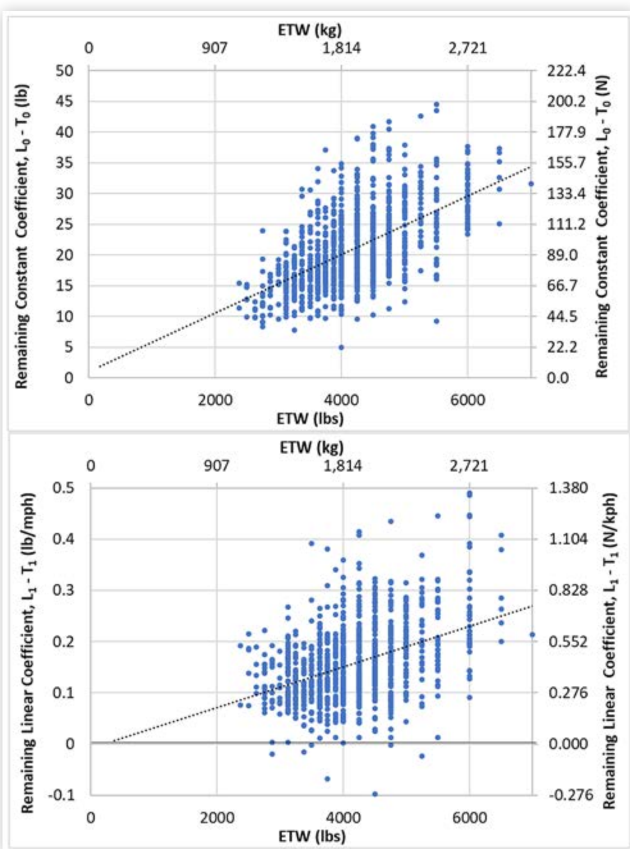


FIGURE 20 The remaining vehicle constant (L_0 - T_0) and linear coefficients (L_1 - T_1) shown as a function of ETW for non-AWD and 4WD vehicles only. Linear trend lines are shown.



both applied tires and weight distribution, the resulting data show expected trends. For both coefficients, the coefficient increases with vehicle weight, as the frictional force scales with the normal force (i.e., weight). Moreover, the increase is near perfectly proportional to vehicle ETW, with the trend lines passing close to the origin.

The fleet data from Figure 19 show a ratio of linear to constant rolling resistance coefficients of 0.165 lbs/mph / 23.5 lbs = 0.00702 mph^{-1} (0.455 N/kph / 104.5 N = 0.00436 kph^{-1}). Although tires on different vehicles in the fleet likely have different characteristic speed effects, and other sources of variability change from test to test and from vehicle to vehicle, this ratio of coefficients should be a reasonable representation of the average value over the fleet.

Thus, it was assumed that the total rolling resistance force (i.e., the sum from both axles) for all vehicles can be represented as a constant and linear term with the ratio given above. Each term is made up of two sections, one arising from the vehicle coefficients (T_1 - L_1 and T_0 - L_0) and one arising from the set coefficients (for convenience designated R_{D0} and R_{D1}). Thus, the proportion of the set coefficients allocated to the rolling resistance is estimated as:

$$\left(L_1 - T_1 + R_{D1}\right) \big/ \left(L_0 - T_0 + R_{D0}\right) = 0.00702\ \text{mph}^{-1} \tag{5}$$

$$\left(L_1 - T_1 + R_{D1}\right) \big/ \left(L_0 - T_0 + R_{D0}\right) = 0.00436\ \text{kph}^{-1}$$

Since the vehicle loss (L) and transmission (T) coefficients are already known, Equation (5) gives one relationship between R_{D0} and R_{D1} which can be used later.

Aerodynamic Losses

To obtain a second relationship between R_{D0} and R_{D1}, the aerodynamic loss coefficients must be determined. Although the assumption is that the aerodynamic losses are purely quadratic, the associated coefficients may exhibit a slight variation (as demonstrated in Figure 18) due to test-to-test variability.

However, if the constant and linear aerodynamic coefficients are non-zero, they should be in a fixed proportion to each other for the resulting second order function to best approximate a purely quadratic curve. Using six data points evenly spaced between 15 and 65 mph (24 to 105 kph) (i.e., at the speed intervals shown in Figure 18), the relationship between the constant and linear aerodynamic coefficients which minimizes error in a quadratic regression is where:

$$\begin{aligned} A_0 &= -17.1 A_1 \left(\text{English}\right) \\ A_0 &= -27.5 A_1 \left(\text{SI}\right) \end{aligned} \tag{6}$$

From these, the best-fit purely quadratic expression is:

$$\begin{aligned} -17.1A_1 + A_1V + A_2V^2 &\approx \left(A_1/82.7 + A_2\right)V^2 \left(\text{English}\right) \\ -27.5A_1 + A_1V + A_2V^2 &\approx \left(A_1/133 + A_2\right)V^2\ \left(\text{SI}\right) \end{aligned} \tag{7}$$

The three dyno set coefficients can now be divided into aerodynamic and rolling resistance losses (from Equation 2). Since there is no quadratic rolling resistance term, the set coefficients can be seperated using the relationship in Equation (6):

$$\begin{aligned} D_2 = A_2,\ D_1 = A_1 + R_{D1},\ D_0 = -17.1\ A_1 + R_{D0}\ \left(\text{English}\right) \\ D_2 = A_2,\ D_1 = A_1 + R_{D1},\ D_0 = -27.5\ A_1 + R_{D0}\ \left(\text{SI}\right) \end{aligned} \tag{8}$$

Combining Equation (8) and Equation (5) produces four equations with four unknowns, which can easily be combined; for example:

$$A_0 = 0.1071[L_0 - T_0 + D_0 - 142(L_1 - T_1 + D_1)] \text{ (English)} \quad (9)$$

$$A_0 = 0.1071\left[L_0 - T_0 + D_0 - 229\left(L_1 - T_1 + D_1\right)\right] \text{ (SI)}$$

The remaining unknown coefficients can be calculated directly from Equations (5), (6), and (8).

Resultant Distribution of Rolling Resistance in the Fleet

The total rolling resistance losses from both the drive and non-drive axles can be transformed to something analogous to the coefficient of rolling resistance (*Crr*) by adding the constant coefficients together to produce a total R_0 and dividing by the equivalent test weight (ETW) of the vehicle in pounds-force or Newtons.

Because the rolling resistance from both axles is totalized, there is no need to differentiate between vehicles tested on two- and four-wheel drive dynamometers, and the rolling resistance calculations were applied to all 1169 vehicle tests in the original data set. The resulting total approximate *Crr* for all 1169 tests is shown in Figure 20 as a function of vehicle's engine power/ETW ratio.

Because a portion of the rolling resistance is speed-dependent, the total *Crr* at higher vehicle speeds will change. However, because the assumption is that the velocity-dependent portion of the rolling resistance is proportional to the constant portion, the overall *Crr* will change by the same proportion for all vehicles. For example, the *Crr* at 50 mph (80 kph) is shown in Figure 21.

The value calculated for *Crr* at 0 speed averages about 0.0086 across all tests, while the average at 50 mph (80 kph) is about 0.0116. These values include actual tire rolling resistance, as well as minor brake and driveline effects, and thus seem to be within a reasonable range. The apparent sensitivity to vehicle power/weight ratio, as seen by the regression lines in Figures 20 and 21, could indicate one of two things. First, more powerful vehicles tend to have wider tires with larger side walls and thus higher rolling resistance. Alternatively, those same vehicles also tend to have larger brakes, driveline, and bearings, which would also increase the minor losses that are lumped into the tire rolling resistance term.

FIGURE 20 Coefficient of rolling resistance (*Crr*) as a function of engine power/weight ratio at zero vehicle velocity.

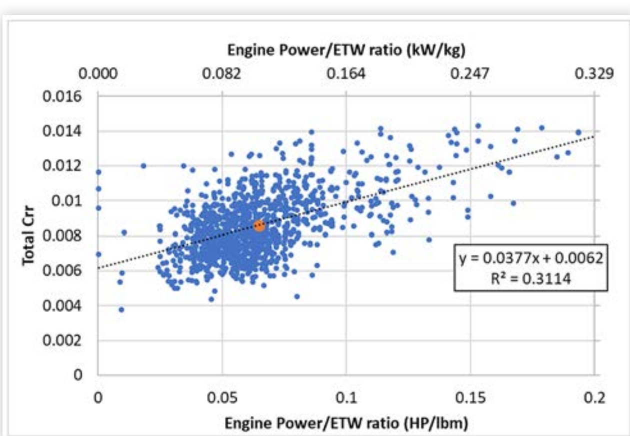
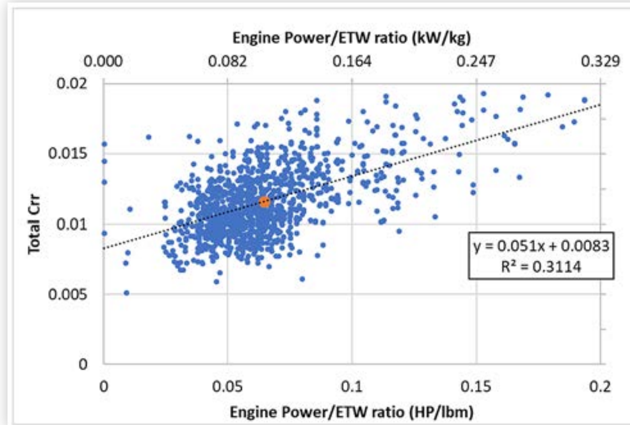


FIGURE 21 Coefficient of rolling resistance (*Crr*) as a function of engine power/weight ratio at 50 mph (80 kph).



Resultant Distribution of Aerodynamic Losses in the Fleet

For the aerodynamic losses, an effective quadratic "aero coefficient" can be calculated from Equation (7), which combines the aerodynamic losses into a single quadratic term. This aero coefficient can be compared for select vehicles having the same body style, but different powertrain components (and thus different test coefficients). The resulting values can be compared to aerodynamic loads estimated in a simpler way, by using either the target quadratic coefficient (F_2) or the set quadratic coefficient (D_2) directly.

As an informal investigation, the vehicles in the MY 2019 database were grouped by name. Each group contained vehicles with the same name, but different engines, transmissions, ETWs, rear end ratios, hybridization components, or other variations likely unrelated to body style. No attempt was made to verify that all configurations within each group did indeed have the same drag coefficient and frontal area (and thus the same aerodynamic drag force), although most configurations are presumably close enough that the aerodynamic losses should be similar.

This informal analysis resulted in approximately 150 groups of vehicles containing three configurations or more. For all these groups, the coefficient of variation (COV) of the target quadratic coefficient (F_2), dyno set quadratic coefficent (D_2), and the aerodynamic coefficient was then calculated.

The average COV of the target and dyno set quadratic coefficients were 6.8% and 7.8%, respectively, while the average COV of the aero coefficient was 3.3%. The COV for the aero coefficient was reduced over two percentage points for over half of the groups, compared to the target or set, and was increased over two percentage points in only four cases.

The most significant improvements occurred in nine groups of vehicles where the COVs of the target and/or dyno set quadratic coefficient exceeded 20%. Table 2 lists these vehicles, along with the COVs of the target quadratic coefficient, dyno set quadratic coefficient, and aerodynamic coefficient. Some, although not all, of these vehicle groups contain individual vehicles with linear vehicle loss coefficients (L_1) which are at the ends of the range seen in the fleet. For example, some configurations of the Honda Civic and Accord vehicles contain CVTs with a corresponding vehicle linear coefficient near or below -1.0 lb/mph (-2.76 N/kph), while some Chevrolet Camaro configurations contain 10-speed ATs with vehicle linear coefficients above 0.80 lb/mph (2.21 N/kph).

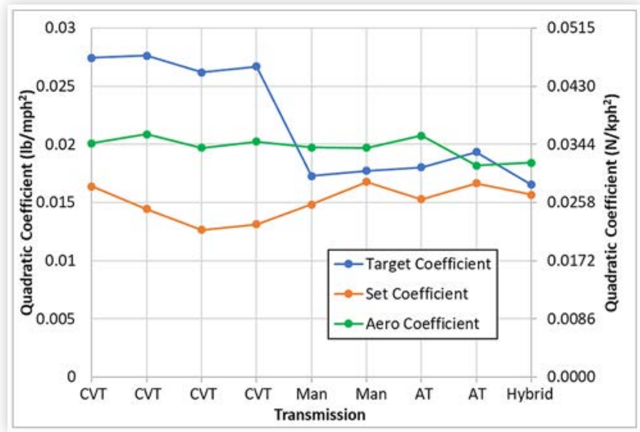
Thus, these vehicle groups are substantially ones where the magnitudes of the transmission coefficients for one or more of the individual vehicles is relatively large. As an example of the relationship between transmissions and the calculated coefficients, Figure 22 shows the target quadratic coefficient (F_2) and the set quadratic coefficent (D_2), along with the aerodynamic coefficient calculated by the process outlined in this paper, for the nine Honda Accord vehicle tests included in the MY 2019 data and in Table 2.

For the Honda Accords in Figure 22, the quadratic target coefficient varied considerably. The set coefficient varied less, but the calculated aero coefficient is noticeably more consistent than either. As this was only an informal investigation, it is possible that some of the remaining variation within this group (and other groups) is due to actual variation in the drag coefficient of individual configurations. For example, some hybrid configurations have additional underbody panels or other aerodynamic elements which reduce their aerodynamic drag.

TABLE 2 COVs of aero estimations of selected vehicle models, including the target quadratic coefficient (F_2), dyno set quadratic coefficent (D_2), and the aerodynamic coefficient (Equation 7). The highlighted Honda Accords are shown individually in Figure 22.

Vehicle Name	No. of Vehicles	Target COV	Set COV	Aero COV
BMW 430i Gran Coupe	4	11.6%	20.0%	2.5%
Dodge Charger	4	23.2%	15.2%	2.8%
Chevrolet Camaro	15	15.2%	23.1%	3.3%
Honda Accord	9	22.5%	9.8%	4.7%
Honda Civic 2dr Coupe	7	11.9%	26.2%	7.3%
Honda Civic 4dr Sedan	6	11.1%	23.6%	4.1%
Genesis G70	9	24.3%	14.6%	9.5%
Hyundai Sonata	7	7.0%	20.5%	3.1%
Toyota Avalon	5	9.8%	21.2%	3.8%

FIGURE 22 Target, dyno set, and "aero" coefficients for nine MY2019 Honda Accord vehicle tests of different configurations. The COVs for each are given in the highlighted line in Table 2.

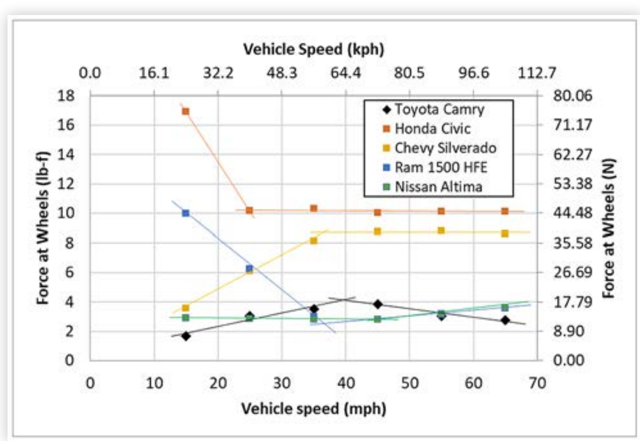


Discussion and Sensitivity

The methodology derived in this paper is based on the predictable relationships seen among transmission coefficients, and by extension the vehicle loss coefficients. The repeatability of these relationships is due to the methodology of defining the second-order function, and to the characteristics of the transmissions themselves. For example, Figure 23 collects the data points used to construct the second-order representations of the five transmissions tested (from Figures 4 through 8), adjusted to 80 - 85 °C for consistency.

For each of these transmissions, the six data points form two intersecting lines, of which one is nearly horizontal. This is reflective of the bifurcated operation noted for some of the

FIGURE 23 Data points from Figures 4 through 8, adjusted to 80 - 85 °C for consistency and approximated with two straight lines.



tested transmissions earlier in this paper. With the six data points located at velocities of 15 mph (24 kph), 25 mph (40 kph), and so on, as in Figure 23, the form of the quadratic regression is quite predictable. For the case where the first two points form a separate line (as for the Honda transmission in Figure 23), the ratio between T_2 and T_1 is -96 mph (-154 kph). For the case where the first three points form a separate line (as for the Ram, Chevy, and Toyota transmissions), the ratio is -103 mph (-165 kph). Unsurprisingly, these numbers are quite close to (and bracket) the ratio of -99 mph (-159 kph) from Equation (3). The regularity of the data in Figure 13 suggests the relationships among transmission coefficients observed in Figure 23 holds as a general rule among nearly all vehicles in the fleet.

Rolling Resistance Speed Dependency

For ease of developing the methodology in this paper which separates rolling resistance and aerodynamic losses, the rolling resistance was assumed to be linear with speed, and thus the "leftover" linear coefficient seen in Figure 11 is associated wholly with rolling resistance. However, it is plausible that the rolling resistance contains non-linear terms [18 - 21], and/or the curve fit may make the coefficient allocation uncertain. To determine whether the assumption of linearity substantially affects the final results, the methodological derivation presented in this paper was repeated, but with the alternate assumption that tire rolling resistance had no linear term, and instead only contained constant and quadratic terms.

When the alternate assumption was applied to the MY 2019 fleet, the resulting calculated aero coefficients differed on average by 0.5% from the original values, with no individual coefficient changing by more than 2% from its original value.

As might be expected, the calculation of rolling resistance was more sensitive to this change in assumptions. Because the actual form of the rolling resistance speed dependency changed, the effect of changing assumptions also depended on the vehicle speed chosen. The calculated *Crr* at zero speed (as shown in Figure 20) increased by about 4% throughout the fleet, while the calculated for *Crr* at 50 mph (80 kph) decreased by about 8.5%.

The "crossover" point, where the calculated *Crr* remained the same, on average, was at about 20 mph. The effect on individual vehicles did vary; however, the effect was generally similar throughout the fleet: over 1000 of the 1169 vehicles had calculated *Crr* values which changed by less than 5% of the fleet mean, and only about 20 vehicles changed by over 10%.

Disregarding Transmissions in Aero Estimation

An important factor in developing the aero coefficients for vehicles is the use of Equation (8) to account for small variability in the data used in the quadratic regression. As an alternative approach, the effect of the transmission in the derivation can be ignored. In this case, either the target or dyno set coefficients could be used directly in Equation (8) to estimate the aero coefficient.

This simplification was performed to produce set-based and target-based aero coefficient approximations, and the results compared over the same approximately 150 groups of vehicles examined previously. For these groups, the average COV of the target-based aero coefficient was reduced from 6.7% to 3.5%, while the average COV of the dynamometer set-based aero coefficient was reduced from 7.8% to 3.5%. This represents a substantial proportion of the reduction seen when including the transmission effects, where the average COV of the aero coefficient was 3.3%.

However, the magnitudes of the aero coefficient approximations calculated using only dyno set or target coefficients are generally higher than the aero coefficients calculated when including the transmission effects, as the transmission losses have not been subtracted from the total loss coefficients. In fact, the target-based aero coefficients are on average 12% higher, and the dyno set-based aero coefficients are on average 4% higher, than the aero coefficient calculated using the transmission effects.

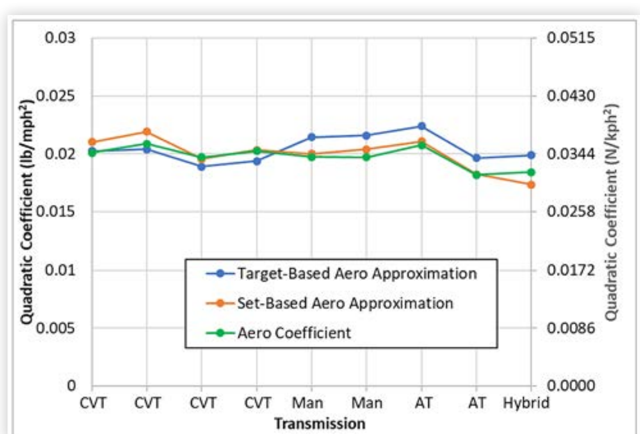
As an example, the set-based and target-based aero coefficient approximations were calculated for the same Honda Accord group shown in Figure 22. The results are shown in Figure 24.

For the Accord, the set-based aero coefficient had a COV of 7.2% and the target-based aero coefficient had a COV of 5.6%, compared to the previously-calculated aero coefficent COV of 4.1%. Both the set-based and target-based aero coefficients are on average higher than the previously-calculated aero coefficent, although the difference for this group is relatively small compared to the 4% and 12% differences across all groups.

Future Work

During the development of the loss separation process, some assumptions were made about the form and magnitude of the losses that enabled losses for individual vehicles to be estimated based on fleet-wide parameters. An advantage of this method is that it requires no additional information about

FIGURE 24 Target-based aero approximation, set-based aero approximation, and the aero coefficients for nine MY2019 Honda Accord vehicles and vehicle tests of different configurations. Compare these data to Figure 22.



individual vehicles to perform the estimation, beyond their target and dyno set coefficients.

However, the estimates could likely be improved if the process were refined to incorporate additional information about vehicle components. For example, one area of potential refinement is in the estimation of transmission coefficients. Although the linear (T_1) and quadratic (T_2) coefficients appear to be strongly linked (see Figure 9), the relationship to the constant coefficient (T_0) is less well defined (see Figure 10). The determination of this coefficient essentially trades off the estimation of losses associated with the transmission with losses associated with rolling resistance.

There may be characteristics of the transmission or vehicle which can be shown to influence the magnitude of the T_0 coefficient, and/or its relationship to the other two transmission coefficients. For example, the vehicle ETW, engine power, or transmission type (CVT versus MT versus AT) may all tend to affect the transmission coefficients, and T_0 specifically, in different ways. This may be particularly true of BEVs, which generally do not contain traditional transmissions. Additionally, the drive system (two- versus four- or all-wheel drive) is likely to affect the magnitude of the T_0 coefficient. Should this work be extended to vehicles of much different scale (to heavy trucks, for example, or very light single-person vehicles), the losses calculated may have to be estimated separately using a different data set. With further work, the relationship between the linear (T_1) and constant (T_0) coefficients (from Figure 10) could be altered to incorporate other transmission and vehicle characteristics.

Another potential area for improvement would be to refine the characterization of the "minor losses," which this analysis has simply assumed are small compared to other losses. Minor losses are substantially contained within the calculation for rolling resistance, and thus the calculated coefficient of rolling resistance (see Figures 20 and 21, for example) contains these minor losses in addition to rolling resistance from the tires. A better estimation of the minor losses, their relative magnitudes, and their relationship to vehicle ETW or engine power may help better define their effects, and in turn better define the losses explicitly due to tires.

A final area of potential improvement is the assumption of the velocity dependence of the rolling resistance term. The methodology developed within this paper used a single relationship between the linear to constant rolling resistance coefficients which was applied to every vehicle within the fleet. This relationship could likely be modified based on tire size, engine power, or other vehicle attributes to more accurately assess the rolling resistance of individual vehicles.

Conclusion

This paper looks at the influence of the transmission on the coastdown coefficients of a vehicle by first looking at the drag losses of five transmissions as a function of speed, and the equivalent quadratic expressions for these losses. For some of these tested transmissions, the data show that the losses are not necessarily well-approximated by the quadratic form which is used to express vehicle coastdown losses. However, when transmission drag losses are converted into a second-order expression, the relationships among the coefficients are predictable, and these relationships are echoed in the relationships among vehicle loss coefficients seen in the fleet.

These relationships can be used to identify transmission losses, and thereby separate vehicle road load losses into constituent components. A methodology is proposed in this paper where the transmission losses are eliminated from the vehicle coastdown losses, leaving only rolling resistance and aerodynamic losses, which can be more easily seperated using a few basic assumptions. This methodology is easily implemented across a range of vehicles, without the need for any additional information on individual vehicles.

The importance of accounting for transmission losses, and their effect on the coastdown coefficients, is particularly noticeable in those cases where the transmission coefficients are large in magnitude. The wide range of transmissions coefficients can noticeably affect the magnitudes of the individual coastdown and dynamometer coefficients, as changes in transmission activity alter the losses as a function of speed, thus changing the shape of the curve fit.

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Nomenclature

Force coefficients in this paper are designated, generically, as C_0, C_1, and C_2, following the nomenclature in reference [2], where the total force = $C_0 + C_1V + C_2V^2$, with V indicating vehicle velocity. To differentiate among coefficients resulting from different loss sources, the following letters are used in place of C:

- D_0, D_1, and D_2: Dyno set (dyno) coefficients
- F_0, F_1, and F_2: Target coefficients
- L_0, L_1, and L_2: Vehicle (loss) coefficients
- T_0, T_1, and T_2: Transmission coefficients
- R_0, R_1, and R_2: Rolling resistance coefficients
- R_{D0}, R_{D1}, and R_{D2}: Portion of the rolling resistance coefficients included in the dyno set coefficients
- R_{T0}, R_{T1}, and R_{T2}: Portion of the rolling resistance coefficients included in the vehicle coefficients
- A_0, A_1, and A_2: Aerodynamic loss coefficients

Contact Information

Andrew Moskalik
National Center for Advanced Technology
US EPA - National Vehicle and Fuel Emissions Laboratory
2565 Plymouth Rd., Ann Arbor MI 48105
moskalik.andew@epa.gov

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Disclaimer

Acronyms and Abbreviations

4WD - four-wheel drive

AT - automatic transmission

AWD - all-wheel drive

BEV - battery electric vehicle

CAN - controller area network

COV - coefficient of variation
Crr - coefficient of rolling resistance
CVT - continuously variable transmission
DCT - dual-clutch transmission
dyno - abbreviation of “dynamometer”
EPA - Environmental Protection Agency
ETW - equivalent test weight
FWD - front-wheel drive
kph - kilometers per hour
mph - miles per hour
MT - manual transmission
MY - model year
RWD - rear-wheel drive

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