SURFACE VEHICLE RECOMMENDED PRACTICE

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(R) Chassis Dynamometer Simulation of Road Load Using Coastdown Techniques

RATIONALE

This procedure has been revised to harmonize terminology across related SAE documents with the latest regulatory test procedure references. Clarifications were made to calculation definitions, computations, and evaluation of results as well as clarifying the text where definitions are referenced. Equations were reorganized to maintain consistency across the document. A spreadsheet based tool was developed that can be used to provide an evaluation reference for the calculation procedure, or to provide a step-by-step calculation verification for existing software.

FOREWORD

Electric chassis roll dynamometers provide the means for rapid, accurate, automatic adjustment of dynamometer loading to simulate vehicle road load over the entire speed range through which the vehicle is tested. Precise calibration of chassis roll torque measurement and speed instrumentation, accurate measurement of base inertia, and controls employing valid algorithms have resulted in accurate dynamometer load coefficient measurements using coastdown techniques without requiring onerous computation and data manipulation by users. Variability of each dynamometer and between dynamometers is low, permitting load coefficients obtained on one dynamometer to be used on other similar dynamometers. To achieve this interchangeability of loading coefficients, operational factors are specified with the objective of keeping test variability at the low levels of the dynamometer.

This procedure was originally developed in conjunction with the introduction of the 120 cm (48 inch) diameter single-roll electric dynamometer for vehicle emissions and fuel economy testing; however, the methodology is applicable to any dynamometer capable of carrying out the road load derivation described, regardless of roll size, geometry, or roll surface roughness, and is intended to provide a standard of best practice for all vehicle testing requiring accurate road load simulation.

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1. SCOPE

This procedure covers vehicle operation and electric dynamometer (dyno) load coefficient adjustment to simulate track road load within dynamometer inertia and road load simulation capabilities.

1.1 Purpose

To provide a uniform procedure for adjusting an electric chassis roll dynamometer to provide accurate simulation of the resistance that must be overcome by the vehicle powertrain to maintain steady speed on a flat road, as determined by track coastdown tests on that vehicle.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 CFR Publications

Available from www.ecfr.gov.

40 CFR §1066 Subpart C, "Dynamometer Specifications"

40 CFR §1066 Subpart D, "Coastdown"

HWFET, Highway Fuel Economy Test, 40 CFR Part 600 "Fuel Economy and Greenhouse Gas Exhaust Emissions of Motor Vehicles", Subpart B "Fuel Economy and Carbon-Related Exhaust Emission Test Procedures" and Appendix I "Highway Fuel Economy Driving Schedule"

2.1.2 Other Publications

Dynamometer Performance Evaluation and Quality Assurance Procedures (AMA) for a 48 inch Single Roll, Electric Light Duty Chassis Dynamometer, March 2000

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1263 Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques

SAE J2263 Road Load Measurement Using Onboard Anemometry and Coastdown Techniques

Brownell, C., Brownell, C., D'Angelo, S., Fagerman, T. et al., "Simulation of 8.65″ Uncoupled Twin-Roll Hydrokinetic Dynamometer Operation on a 48″ Single-Roll Electric Dynamometer," SAE Technical Paper 940486, 1994, https://doi.org/10.4271/940486.

D'Angelo, S., Mears, W., and Brownell, C., "Large-Roll Chassis Dynamometer with AC Flux-Vector PEU and Friction-Compensated Bearings," SAE Technical Paper 930391, 1993, https://doi.org/10.4271/930391.

DeRaad, L., "The Influence of Road Surface Texture on Tire Rolling Resistance," SAE Technical Paper 780257, 1978, https://doi.org/10.4271/780257.

Mears, W., D'Angelo, S., and Paulsell, C., "Performance Tests of a Large-Roll Chassis Dynamometer with AC Flux-Vector PEU and Friction-Compensated Bearings," SAE Technical Paper 930392, 1993, https://doi.org/10.4271/930392.

Metz, L., Akouris, C., Agney, C., and Clark, M., "Moments of Inertia of Mounted and Unmounted Passenger Car and Motorcycle Tires," SAE Technical Paper 900760, 1990, https://doi.org/10.4271/900760.

Oswald, A. and Browne, L., "The Airflow Field Around An Operating Tire and Its Effect on Tire Power Loss," SAE Technical Paper 810166, 1981, https://doi.org/10.4271/810166.

2.2.2 Other Publications

Differential and Integral Calculus, C. E. Love, Macmillan Co., 1948

3. DEFINITIONS

3.1 AVERAGE DECELERATING FORCE (F_{AVG})

The average force over a coastdown speed interval, determined from Newton's second law as:

$$F_{\mathrm{AVG}} = M_E \frac{\Delta \mathrm{V}}{\Delta \mathrm{t}} \quad \text{(Eq. 1)}$$

3.2 BASE INERTIA (I_B)

The rotational inertia of the rotating dynamometer components between the vehicle driving tires and the dynamometer torque-measuring device. For an in-line rotating torque-meter, 50% of the torque-meter's inertia should be included.

3.3 COASTDOWN SPEED INTERVAL

The range of speeds during a coastdown event defined by an upper and lower speed.

3.4 COASTDOWN SPEED RANGE

The coastdown speed range is the complete speed range over which data is evaluated, comprised of multiple contiguous speed intervals. The coastdown speed range starts at the upper speed of the highest-speed coastdown speed interval and ends at the lower speed of the lowest-speed coastdown speed interval.

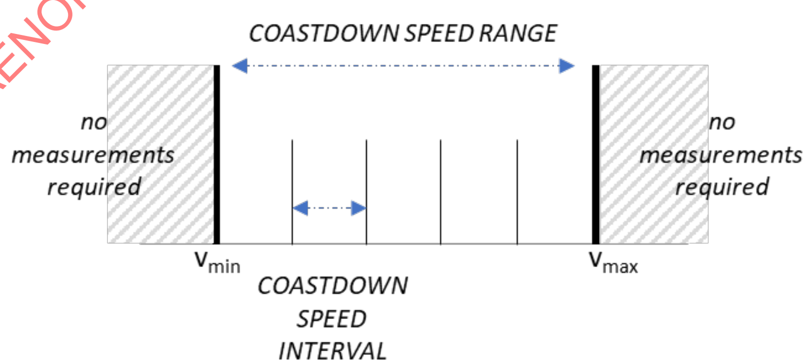

Figure 1 - Coastdown speed range and speed intervals

3.5 DRIVETRAIN

The rotating components of a vehicle mechanically connected to the driving wheels when the transmission is in neutral gear or mode. This includes the tires, wheels, brake disks/drums, drive shafts, differential, propeller shaft, transmission output shaft, and some components within the transmission.

3.6 DYNAMOMETER CALIBRATION

The adjustment and verification of the accuracy of dynamometer time, speed, and load instrumentation, base inertia determination, mass simulation, and road load simulation. These procedures can be performed at the intended test cell temperature range of 20 to 30 °C. Refer to 40 CFR §1066.215 "Summary of verification procedures for chassis dynamometers" for a list of verifications necessary for performing the procedures outlined in this document.

3.7 UNLOADED COASTDOWN

A calibration verification coastdown that is performed without a vehicle on the dynamometer. This procedure is typically performed in order to verify the simulation accuracy of the dynamometer.

3.8 EQUIVALENT TEST WEIGHT (ETW or ETW CLASS)

Test weight, as dictated by U.S. Code of Federal Regulations (40 CFR §1066.805), that is assigned to represent a class of test vehicles. ETW is a weight class and is not necessarily equal to the as-tested weight of a vehicle.

3.9 2WD DYNAMOMETER TESTING

Refers to the use of a dynamometer that includes only the two wheels on one axle as part of the simulation, regardless of the powertrain configuration of the vehicle. In such operation, the remaining wheels will typically be fixed on the laboratory floor.

3.10 4WD DYNAMOMETER TESTING

Refers to the use of a dynamometer that includes all four wheels as part of the simulation, regardless of the powertrain configuration of the vehicle.

3.11 TEST VEHICLE MASS (M_{VEH})

The mass of an individual test vehicle as determined by weighing, where M_{VEH} is determined following track test mass provisions specified in SAE J2263.

NOTE: Regulatory testing uses weight classes, not individual vehicle test mass.

3.12 EQUIVALENT MASS OF ROTATING COMPONENTS (M_R)

The contribution of rotational inertia to the resistance of the vehicle to longitudinal motion (e.g., wheels, axles). For light-duty vehicles, the rotational inertia per axle is typically estimated to be equal to 1.5% of the vehicle's weight, or in the case of regulatory testing, 1.5% of ETW:

$$M_{\mathrm{R}} = 0.015 \cdot [M_{\mathrm{VEH}} \text{ or ETW}] \text{ per axle} \quad \text{(Eq. 2)}$$

This estimate is applicable for vehicles with single, normal-sized wheels, but not for vehicles with driveline components which are likely to result in an effective rotational inertia greater than 1.5% per axle, such as dual-wheel trucks, or hybrid/battery electric vehicles with larger than normal rotational inertia. These vehicles require a more appropriate estimation or determination of the actual effective mass of the rotating drivetrain components. Axle-specific naming conventions for M_R are given below:

M_{R_D} = M_R for the drive axle (2WD dynamometer testing)

M_{R_ND} = M_R for the non-drive (static) axle (included for 4WD dynamometer testing)

M_{R_T} = total rotating axle/wheel mass = M_{R_D} for 2WD dynamometer testing
= M_{R_D} + M_{R_ND} for 4WD dynamometer testing or track testing

3.13 EFFECTIVE TEST-TRACK MASS (M_{TE})

The effective mass of an individual test vehicle, including the vehicle's mass plus the equivalent mass of the wheels, tires, and other rotating components:

$$M_{TE} = M_{VEH} + M_{R\_D} + M_{R\_ND} \quad \text{(Eq. 3)}$$

Using Equation 2 to estimate the equivalent mass of rotating components of the front and rear axles, M_{TE} can be calculated as follows:

$$M_{TE} = 1.03 \cdot M_{VEH} \quad \text{(Eq. 4)}$$

3.14 DYNAMOMETER SET INERTIA (M_{SET})

The setting that specifies the inertia that is to be simulated by the dynamometer. The appropriate method for determining M_{SET} depends on the testing intent as described in 3.14.1 and 3.14.2.

3.14.1 GENERAL EXPERIMENTAL TESTING: SIMULATION OF INDIVIDUAL TEST VEHICLE WEIGHT

For general experimental testing, the dynamometer must simulate the linear inertia of the test vehicle in addition to the rotational inertia of the rotating components that are not rotating as part of the simulation on the dynamometer during testing. For 2WD dynamometer testing, M_{SET} equals the test vehicle mass (M_{VEH}) plus the equivalent mass of rotating components of the non-drive axle (M_{R_ND}). Using Equation 2 (see 3.12) for M_R, M_{SET} for 2WD dynamometer testing is:

$$M_{Set\ 2WD} = 1.015 \cdot M_{VEH} \quad \text{(Eq. 5)}$$

For 4WD dynamometer testing, all vehicle rotating components are rotating on the dynamometer as part of the simulation during testing, so the dynamometer does not need to simulate the inertial contribution of those components. M_{SET} equals the test vehicle mass:

$$M_{Set\ 4WD} = M_{VEH} \quad \text{(Eq. 6)}$$

3.14.2 REGULATORY TESTING: SIMULATION OF VEHICLE WEIGHT CLASS

This case applies to regulatory testing that is based on a vehicle's ETW class as dictated by U.S. Federal Register 40 CFR §1066.805, and 40 CFR §1066.201 through §1066.290. For 2WD dynamometer testing for regulatory purposes, M_{SET} equals the ETW class:

$$M_{Set\ 2WD} = \text{ETW} \quad \text{(Eq. 7)}$$

In order to achieve the same total inertial load for the vehicle-dynamometer system in 2WD and 4WD dynamometer testing (M_E, Equation 9), M_{SET} for 4WD dynamometer testing must be set equal to the ETW class minus the equivalent mass of rotating components of the non-drive axle of the vehicle during 2WD dynamometer testing (M_{R_ND})." Using Equation 2, M_{SET} for 4WD dynamometer testing is:

$$M_{Set\_4WD} = 0.985 \cdot \text{ETW} \quad \text{(Eq. 8)}$$

3.15 EFFECTIVE TEST MASS (M_E)

Effective test mass (M_E) is the total effective linear inertia associated with the vehicle-dynamometer system. ME is the sum of (1) dynamometer set inertia (M_{SET}, Equations 5 through 8), and (2) the equivalent mass of rotating components (M_R):

$$M_E = M_{Set} + M_{R\_T} \quad \text{(Eq. 9)}$$

where M_{R_T} includes one or two axles (see 3.12) depending on whether the test is conducted as a 2WD or 4WD dynamometer simulation, respectively. M_E is used together with the measured coastdown times in order to calculate the forces acting to decelerate the system during a dynamometer coastdown.

3.15.1 GENERAL EXPERIMENTAL TESTING: EFFECTIVE TEST MASS

Combining Equation 5 (2WD Dynamometer testing) or Equation 6 (4WD Dynamometer testing) with Equation 9 results in effective test mass for general experimental testing being equivalent to the effective test-track mass defined in Equation 4.

$$M_E = M_{TE} = 1.03 \cdot M_{VEH} \quad \text{(Eq. 10)}$$

3.15.2 REGULATORY TESTING: EFFECTIVE TEST MASS

Using Equation 2, Equation 9 can be written, for 40 CFR §1066.201 through §1066.290 regulatory testing as follows:

$$M_E = 1.015 \cdot \text{ETW} \quad \text{(Eq. 11)}$$

Because M_{Set_4WD} is defined as 0.985 x ETW in Equation 8, and M_{Set_2WD} is defined as ETW in Equation 7, the total inertia load is the same for 4WD and 2WD test modes when defined in terms of ETW, ($M_{E\_4WD} = M_{E\_2WD}$) and Equation 11 applies to both 2WD and 4WD dynamometer testing.

3.16 FORCE COEFFICIENTS

Several specific sets of force coefficients are used, each of which describes a second-order force-versus-speed relationship. A generic set is represented as C_x, where the subscript "x" refers to the entire set of three coefficients, individually designated as C_0, C_1, and C_2. The force at speed V is calculated as $C_0 + C_1V + C_2V^2$. Each specific set of coefficients is represented by a different letter.

3.16.1 DYNO TARGET COEFFICIENTS: F_x (F_0, F_1, and F_2)

The target coefficients describe the total force (tire, drivetrain, and aerodynamic drag) acting to decelerate a vehicle during a test-track coastdown. These coefficients are developed from track data (or equivalent analytical methodology), corrected to standard conditions, and possibly adjusted to account for differences between test vehicle mass and ETW class assigned for dynamometer testing.

3.16.2 DYNO SET COEFFICIENTS: D_x (D_0, D_1, and D_2)

The set coefficients (also known as A, B, and C, respectively) describe the contribution to the road load force that is simulated by the dynamometer.

3.16.3 DYNO MEASURED (RESULTANT) COEFFICIENTS: R_x (R_0, R_1, and R_2)

The measured coefficients represent the total force acting to decelerate a vehicle during an on-dynamometer coastdown. They represent the combined effects of the set coefficients and the vehicle's own inherent parasitics. These coefficients are computed from the effective test mass (M_E) and the coastdown times measured as the dynamometer-vehicle system coasts through each speed interval. For coastdown calculations with a vehicle on the rolls, M_E is used for mass. For coastdowns without vehicle, the M_{Set} is used.

3.16.4 DYNO VEHICLE (LOSS) COEFFICIENTS: L_x (L_0, L_1, and L_2)

Vehicle coefficients represent a vehicle's drivetrain losses (i.e., parasitic friction) while on the dynamometer. They describe the contribution to a vehicle's road load that does not need to be simulated by the dynamometer. Dyno vehicle loss coefficients are calculated by subtracting the dyno set coefficients from the dyno measured coefficients for a particular coastdown run.

3.17 MID-SPEED FORCE

The force at the midpoint of a speed interval.

3.18 ROAD LOAD DERIVATION

A set of procedures in which the dynamometer conducts coastdown tests with some or all of the vehicle wheels on the rolls and adjusts its set coefficients so that the measured coefficients match the target coefficients. A road load derivation can be performed using either an iterative procedure or a fixed run procedure.

3.18.1 ITERATIVE PROCEDURE

A road load derivation procedure in which the set coefficients are adjusted after each coastdown, based on the measured coefficients for that coastdown.

3.18.2 FIXED-RUN PROCEDURE

A road load derivation procedure in which the set coefficients are fixed at the beginning of the procedure, and vehicle coefficients are determined for a fixed number of coastdowns (at least four coastdowns and average the last three). The final set coefficients are determined from the averaged vehicle coefficients.

3.19 SIMULATION MODE

The operating mode where the dynamometer simulates the vehicle inertia and road load commanded by dynamometer set inertia and the set coefficients so that a vehicle driven on the dynamometer operates as it would on the road.

3.20 POWER INTEGRAL (PI)

The integral of power versus speed over the coastdown speed range. This can be used to compare individual coastdown results during the procedure, to indicate potential problems with the vehicle or dynamometer. The power versus speed relationship is determined from the dyno target coefficients.

3.21 PI METRIC (PIM)

The normalized standard deviation of the power integral values expressed as a percentage of PI_{Target}. The PI metric is calculated using the three runs utilized to calculate the final vehicle coefficients in the fixed-run procedure.

4. EQUIPMENT

4.1 Dynamometer

4.1.1 Requirements for Regulatory Testing

For North American compliance and certification testing, the dynamometer must meet all requirements outlined in 40 CFR, Part 1066, Subpart C - "Dynamometer Specifications."

4.1.2 Recommendations for General Testing

For non-regulatory testing, it is recommended that the dynamometer be able to accelerate the vehicle at approximately 3.6 km/h/s (2.2 mph/s) to a speed 10 km/h (6 mph) above the highest evaluated speed (depicted by V_{max} in Figure 1) during a coastdown procedure. The dynamometer must also be able to utilize software that can perform the automated coastdown algorithms described in this procedure.

a. Roll Diameter: 120 cm or greater

b. Roll Surface Roughness: Surface should represent a dry road and be sufficiently rough to minimize slippage between the tire and roll surface without introducing excessive tire wear.

c. Roll Diameter Tolerance: ±0.254 mm of nominal.

d. Speed Resolution and Accuracy: 0.01 km/h.

e. Time Resolution: 0.01 second.

f. Time Accuracy: 0.001%.

g. Acceleration Accuracy: 1%

4.1.3 Coastdown Load Measurement Requirements

a. Making automatic accelerations at controlled acceleration rate.

b. Initiating, running, and terminating coastdowns using dyno set coefficients to control road load and the inertia setting to control mass simulation throughout the coastdown.

c. Computing measured coefficients.

d. Comparing force curve obtained using measured coefficients to that obtained using target coefficients.

e. Adjusting dyno set coefficients.

f. Determining vehicle coefficients.

g. Displaying, recording, and reporting results.

4.1.4 Coefficient Resolution

Number of decimal digits.

C_0	xxxx.xx N or lbf
C_1	xx.xxxx N/(km/h) or lbf/(mph)
C_2	x.xxxxx N/(km/h)^2 or lbf/(mph)^2
Inertia	1 kg or 1 pound

4.1.5 Motoring Capability

It is recommended that the dyno motoring capacity is sufficient to accelerate dynamometer and vehicle drivetrain to maximum required speed at 3.6 km/h/s ± 0.5 km/h/s (2.2 mph/s ± 0.3 mph/s).

4.1.6 Data Acquisition

Sufficient to record all data required to conduct a complete coastdown road load derivation test.

4.1.7 Computation

As specified under Section 5 and illustrated in Appendix A. A SAE J2264 coastdown calculation tool in spreadsheet format is available which illustrates the calculation sequence.

4.1.8 Unloaded Coastdown

Unloaded coastdown immediately following the derivation is not required for regulatory testing. Calibration may be verified by running an unloaded coastdown immediately following the road load coefficient derivation using the final dynamometer settings and coast speed interval schedule from the road load derivation. The maximum load error at the center of any coastdown speed interval may not exceed ±10 N (2.2 pounds).

4.2 Restraint System

Follow the dynamometer manufacturer instructions to center and restrain the vehicle on the dynamometer. Changes in restraint loading can impact vehicle losses on the dynamometer, and therefore should be avoided. After installation, the restraint system should maintain the centered drive wheel position within the following recommended limits throughout the coastdown portions of the road load derivation. Vehicle automatic ride height adjustment should be disabled during dynamometer testing to ensure constant vehicle position and restraint system forces on the vehicle and dynamometer.

NOTE: If the vehicle is removed from the dynamometer between the road load derivaton and the emissions test, care must be taken to accurately reproduce the vehicle restraint setup that was used for the road load derivation.

4.2.1 Lateral Position (Side to Side)

Vehicle should remain aligned and lateral movement minimized to ensure repeatability.

4.2.2 Longitudinal Position (Front to Rear)

Center of tire contact patch within ±25 mm (1 inch) of top of roll.

4.2.3 Vertical Force

The restraint system should be designed to impose no vertical force on the drive wheels. No more than ±5 mm (0.2 inch) vertical drive axle suspension static deflection should be caused by restraint installation on the vehicle.

4.3 Air Circulation/Cooling

An air circulation and cooling system is required for engine cooling and maintaining repeatable ambient temperature and airflow conditions around the vehicle drivetrain. It is recommended that the test cell ambient temperature not change more than ±5 °C (9 °F) during the warm-up and road load derivation. Air temperature and flow around the vehicle tires and drivetrain will affect warm-up and should approximate those conditions present during subsequent testing using the dyno set coefficients obtained in this derivation. Some exceptions to these temperature and flow recommendations may be permitted by government regulations.

5. COASTDOWN COMPUTATIONS

This section describes calculations which can be used to obtain measured coefficients (R_x) from the data acquired during a coastdown (alternative methods yielding equivalent or more representative results may be used consistent with good engineering judgment). The dynamometer measures speed to 0.01 km/h accuracy during coastdown and records the time to coast through each speed interval (Δt). These coastdown times are used with the effective test mass to calculate the average measured decelerating force over each speed interval. Although it is technically the speed (V), and coast time (Δt) that are measured, the calculated force is referred to as the “measured” force in order to distinguish it from other intermediate force quantities that are calculated as part of the error correction procedure.

The error correction procedure allows the mid-interval “measured” decelerating force to be estimated from the average measured decelerating force for a given interval. First, the set coefficients (D_x) are used to calculate a mid-interval force value and average force value for the interval. The average force value is calculated using an analytically obtained value of coast time (Δt) that is obtained by numerical integration over the speed interval using the set coefficients.

The difference between these calculated forces can then be used as a correction to the average measured decelerating force, providing an approximate mid-interval “measured” decelerating force. A quadratic regression is run on these approximate force values to give approximate measured coefficients (R_{xApp}). The correction procedure is then performed again, except using the approximate measured coefficients instead of the set coefficients. A quadratic regression is run on the resulting mid-speed force values again to provide the final measured coefficients (R_x). A SAE J2264 coastdown calculation tool in spreadsheet format is available which illustrates the calculation sequence.

5.1 Integration for Analytically Obtained Values of Δt

The following integral is evaluated to provide analytically obtained coastdown times throughout the calculations.

$$\Delta t = \int dt = \int_{V_1}^{V_2} \frac{M_E}{F} dV = \frac{M_E}{3.6} \int_{V_1}^{V_2} \frac{1}{C_0 + C_1 V + C_2 V^2} dV \qquad \text{(Eq. 12)}$$

Utilize Simpson's approximation (or other integration method using good engineering judgement) using at least twenty segments covering each speed interval. This computation method is described in 2.2.2 and many other elementary calculus texts.

NOTE: The calculations assume the use of metric units: Mass is expressed in kilograms, force is expressed in Newtons and speed is expressed in kilometers per hour.

5.2 Example Calculation Sequence

The following calculation sequence and step numbers reference the flow chart shown in Figure 2.

1. Calculate $F_{AvgMeas}$ from the coastdown data as:

$$F_{\text{AvgMeas}} = \frac{M_E}{3.6} \frac{\Delta \text{V}}{\Delta \text{t}} \qquad \text{(Eq. 13)}$$

2. Calculate Δt_{Set} by integration as shown in Equation 14:

$$\Delta \text{t}_{\text{Set}} = \frac{M_E}{3.6} \int_{V_1}^{V_2} \frac{1}{D_0 + D_1 V + D_2 V^2} \text{dV} \qquad \text{(Eq. 14)}$$

3. Calculate F_{AvgSet} as:

$$F_{\text{AvgSet}} = \frac{M_E}{3.6} \frac{\Delta \text{V}}{\Delta \text{t}_{\text{Set}}} \qquad \text{(Eq. 15)}$$

This is an average force over the speed interval as calculated using the set coefficients.

4. Calculate F_{MidSet} as:

$$F_{\text{MidSet}} = D_0 + D_1 V_{\text{Mid}} + D_2 V_{\text{Mid}}^2 \qquad \text{(Eq. 16)}$$

This is the force at the mid-point of the speed interval as calculated using the set coefficients.

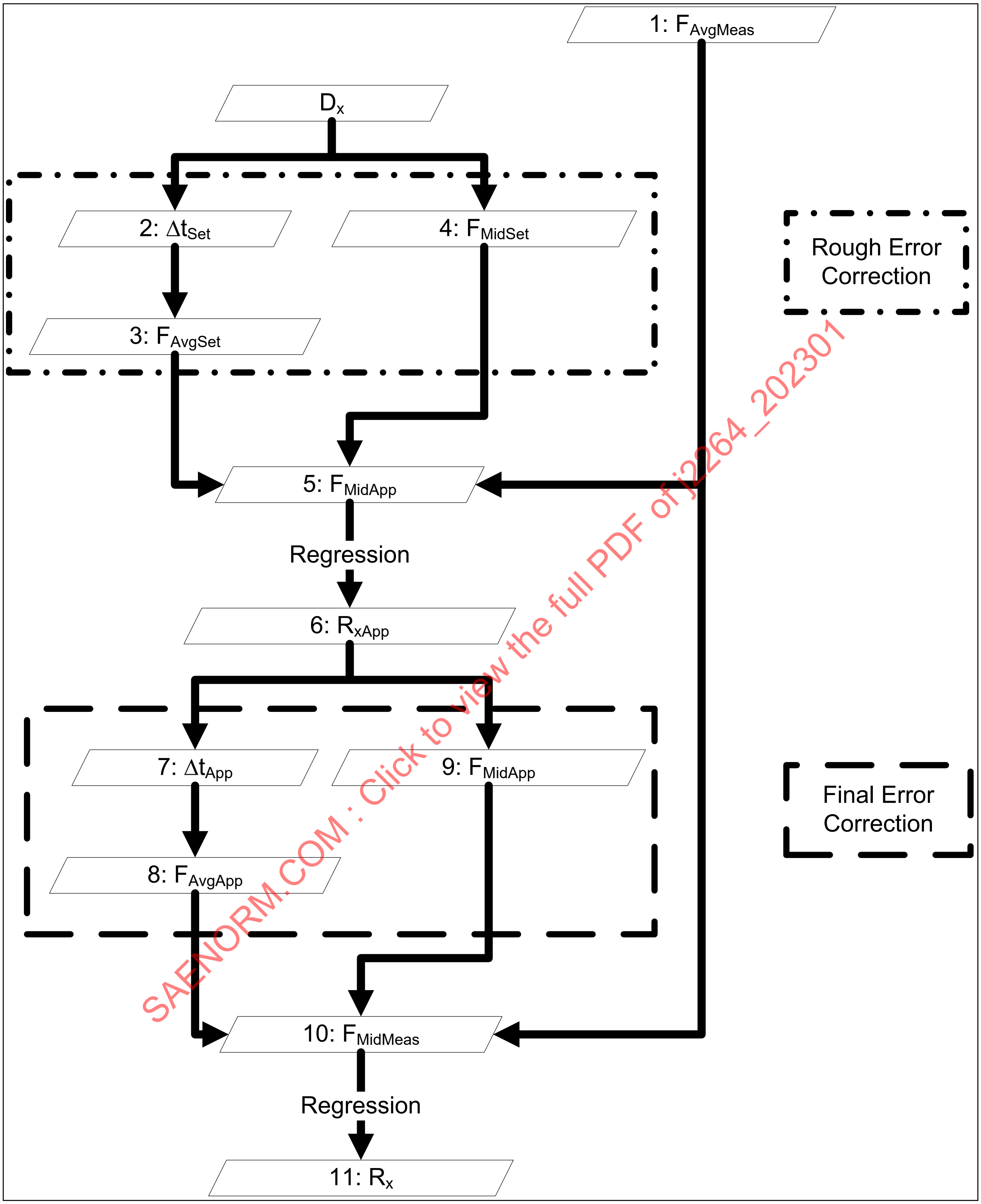

Figure 2 - Flow chart of coastdown calculation and error correction sequence

5. Calculate F_{MidApp} as:

$$F_{\mathrm{MidApp}} = F_{\mathrm{AvgMeas}} - (F_{\mathrm{AvgSet}} - F_{\mathrm{MidSet}}) \quad \text{(Eq. 17)}$$

This is an approximate mid-interval “measured” decelerating force, obtained by correcting the average measured decelerating force using the rough correction obtained from steps 2 through 4.

6. Perform steps 2 through 5 for every speed interval, and then perform a regression on the values of F_{MidApp} versus V_{Mid} to obtain approximate measured coefficients, R_{xApp}.

7. Calculate Δt_{App} by integration as shown in Equation 18:

$$\Delta \mathrm{t}_{\mathrm{App}} = \frac{M_E}{3.6} \int_{V_1}^{V_2} \frac{1}{R_{0\mathrm{App}} + R_{1\mathrm{App}} V + R_{2\mathrm{App}} V^2} \mathrm{dV} \quad \text{(Eq. 18)}$$

8. Calculate F_{AvgApp} as:

$$F_{\mathrm{AvgApp}} = \frac{M_E}{3.6} \frac{\Delta \mathrm{V}}{\Delta \mathrm{t}_{\mathrm{App}}} \quad \text{(Eq. 19)}$$

This is an average force over the speed interval as calculated using the approximate measured coefficients.

9. Calculate F_{MidApp} as:

$$F_{\mathrm{MidApp}} = R_{0\mathrm{App}} + R_{1\mathrm{App}} V_{\mathrm{Mid}} + R_{2\mathrm{App}} V_{\mathrm{Mid}}^2 \quad \text{(Eq. 20)}$$

This is the force at the mid-point of the speed interval as calculated using the approximate measured coefficients.

10. Calculate $F_{MidMeas}$ as:

$$F_{\mathrm{MidMeas}} = F_{\mathrm{AvgMeas}} - (F_{\mathrm{AvgApp}} - F_{\mathrm{MidApp}}) \quad \text{(Eq. 21)}$$

This is the final mid-interval “measured” force for the speed interval, obtained by correcting the average measured decelerating force using the final correction obtained in steps 7 through 9.

11. Perform steps 7 through 10 for every speed interval, and then perform a regression on the values of $F_{MidMeas}$ versus V_{Mid} to obtain the final measured coefficients, (R_x).

12. Once measured coefficients (R_x) are established, evaluate the maximum load error for each speed interval by subtracting the calculated dyno target force (F_x) from the dyno measured force (the final regression curve defined by coefficients (R_x) across speed range.

$$Error = (R_0 + R_1 V + R_2 V^2) - (F_0 + F_1 V + F_2 V^2) \quad \text{(Eq. 22)}$$

It is recommended that the maximum force error between curves for each interval is established using an analytical curve comparison or numerical method utilizing at least twenty segments covering each speed interval. Alternatively, the force error may be calculated at the mid-interval speed. The maximum force error for all speed intervals must be within the allowable limit of ±10 N (2.2 pounds). Force error limits may be expanded at test vehicle mass (ETW for regulatory testing) over 7000 pounds using good engineering judgment.

If the force error is within the allowable limits for all speed intervals throughout the coastdown speed range, the coastdown run passes. If the coastdown run does not pass within the allowable force error limits for all speed intervals, calculate new dyno set coefficients by adding the current dyno set coefficients to the difference between the roadload target coefficients and the dyno measured coefficients:

$$Dx(i+1) = Dx(i) + Fx - Rx(i) \quad \text{(Eq. 23)}$$

6. ROAD LOAD DERIVATION PROCEDURE

6.1 Summary

The vehicle and dynamometer should be conditioned and configured in accordance with 6.2 and 6.6 of this document and preconditioned to stabilize parasitic friction. A pre-test coastdown without a vehicle (unloaded coastdown) may be run to verify dynamometer calibration. The vehicle test weight is adjusted if necessary, it is soaked to test temperature, and tire pressure is set to the specified value. After installation on the dynamometer, two HWFET cycles are driven to warm up the vehicle tires and drivetrain. Then, either the “iterative” or the “fixed-run” derivation procedure is run by the dynamometer to determine the final dynamometer coefficients. For non-regulator testing, other methods and parameters may be used to determine that the vehicle is in a repeatable state (i.e., tire temperature, time at steady state speed, or repeating other driving traces). Care should be taken to use the same criteria for all testing in any given program.

If the vehicle is removed, and an unloaded coastdown may be performed to verify dynamometer calibration. The test results from the dynamometer are stored to archive, and reports generated.

6.2 Recommended Pre-Test Calibration Check

To minimize errors in road load derivation results, it is essential that dynamometer calibration is correct. To verify the dynamometer calibration, the following steps are recommended.

6.2.1 Dynamometer Preconditioning

Follow dynamometer manufacturer’s recommended practice or laboratory procedure to stabilize the dynamometer parasitic friction.

6.2.2 Calibration Verification and Coastdown

For regulatory testing, CFR 40 §1066.215 provides a summary of verification procedures, and §1066.270 defines the requirements for unloaded coastdowns. For non-regulatory testing where the dynamometer is not verified by a similarly robust laboratory quality assurance program, it is recommended that an unloaded coastdown be performed directly following the test using the test coastdown speed intervals with dynamometer set inertia (M_{Set}) and dyno set coefficients (D_x) appropriate for the test vehicle. Run one coastdown test. If maximum load error at any of the mid-interval speed points over the coastdown speed range is greater than ±10 N (2.2 pounds), review the dynamometer for mechanical problems, correct, and re-run coastdowns until the maximum error is less than ±10 N, then re-run the previous road load derivation.

6.3 Vehicle Preparation

6.3.1 Temperature Soak

Soak vehicle and test tires at test temperature ±3 °C (5 °F) for at least 4 hours.

6.3.2 Tire Pressure Adjustment

After tires have soaked for at least 4 hours at test temperature, set tire pressure to manufacturer’s recommendation.

6.4 Dynamometer Set-Up

Initial dynamometer set-up for a light duty vehicle road load derivation consists of selecting a 2WD or 4WD configuration. It is important to verify that the dynamometer setup used while performing a road load derivation matches the dynamometer setup for subsequent tests that utilize the generated coefficients. Some dynamometers may have additional modes (synchronous modes) where the non-drive axle is rotated by the dynamometer but not included in the vehicle simulation, often to alleviate issues with vehicle anti-lock braking or vehicle stability control systems.

NOTE: If the vehicle is removed from the dynamometer between the road load derivaton and the emissions test, care must be taken to accurately reproduce the vehicle restraint setup that was used for the road load derivation.

6.4.1 Estimated Set Coefficients for Vehicle Preconditioning and Initial Coastdown Run (D_{x_EST})

If set coefficients are available from road load derivation results on similar vehicles, use these settings for the simulation mode set up. If none are available, approximate set coefficients may be estimated from the target coefficients as follows:

For regulatory testing on a 2WD dynamometer:

$D_{0\_EST} = 0.5 \times F_0$
$D_{1\_EST} = 0.2 \times F_1$
$D_{2\_EST} = F_2$

For regulatory testing on a 4WD dynamometer:

$D_{0\_EST} = 0$
$D_{1\_EST} = 0$
$D_{2\_EST} = F_2$

6.4.2 Dynamometer Settings for Road Load Derivation

a. Dyno target coefficients (Fx: F0,F1,F2).

b. Dynamometer set inertia (MSet).

c. Effective Mass (ME, typically calculated automatically by the dynamometer software using the MSet).

d. Coastdown Speed Intervals: Set up coastdown speed intervals that cover a coastdown speed range from 115 to 15 km/h (or from 70 to 10 mph). Historically, regulatory testing based on 40 CFR §1066 use 10 mph intervals (approximately 16 km/h), but smaller intervals may be used.

e. Acceleration Rate Between Coastdowns: Set at 3.6 km/h/s (2.2 mph/s). For vehicle-driven accelerations, the minimum average acceleration rate should be greater than 1 mph/s.

f. Force Error (iterative option only): Set the maximum acceptable force difference between the force-versus-speed curves calculated using the target coefficients and the measured coefficients as defined in 5.2.12.

g. Number of Runs: Set the number of coastdown runs to be performed for a valid test.

h. Iterative Procedure: Set the maximum number of runs to be performed, and the required number of verification runs. Recommended values: 15 maximum, two verification runs.

i. Fixed-Run Procedure: Set the number of runs, N, for which vehicle coefficients should be averaged together. Recommended value: At least three consecutive runs (not including initial stabilization run).

6.5 Vehicle Installation on Dynamometer

6.5.1 Restraint and Alignment

Install vehicle as outlined in 4.2.

6.5.2 Vehicle Cooling

Provide vehicle cooling as outlined in 4.3.

6.6 Vehicle Preconditioning

Drive two consecutive HWFET cycles (see 2.1.1) with dynamometer operating in simulation mode. Each HWFET is 16.5 km (10.25 miles) long. Total time is 25 minutes, 28 seconds.

6.7 Road Load Derivation Runs

Start the dynamometer road load derivation procedure within 2 minutes of completing the vehicle preconditioning if possible. If additional time is needed (such as for selecting neutral gear or mode) use good engineering judgement to extend the delay time between the end of preconditioning and the beginning of coast downs.

Any accessories which were operated during test-track coastdowns should be activated, and any operating procedures which may be required for identical engine and transmission operation to that of the test-track coastdown should be carried out. Any vehicle accessory that would interfere with vehicle restraints and affect vehicle loading on the dynamometer (such as active ride height) should be disabled for dynamometer simulation.

A road load derivation “run” is defined by the following sequence:

1. For dynamometer-driven accelerations, the transmission is placed in neutral gear or mode with the engine idling if appropriate. For vehicle-driven accelerations, the vehicle should be placed in the appropriate gear before beginning acceleration and shifted as necessary to continue the acceleration until a speed of 10 km/h (6 mph) above the highest data speed for the vehicle coastdown is attained.

2. For vehicle-driven accelerations, at this point the vehicle should be shifted into neutral gear or mode.

3. The driver must either remain in the vehicle or add appropriate compensating ballast upon exit.

The road load derivation sequence should be performed without interruption.

6.8 Iterative Procedure

The iterative road load derivation procedure is to be performed as follows:

1. For the first run, the dynamometer software will use the set coefficients that represent a best guess for the vehicle. Initial coefficients may be obtained using the method described in 6.4.1.

2. The software will calculate the measured coefficients from the run and compare them to the target values to calculate error as defined in Equation 22. If the curves described by the coefficients agree to within specified limits, the run is considered to “pass.” Otherwise, it is considered to “fail.”

3. If a run fails, the software will quantify the measured coefficients’ difference from the target coefficients, adjust the set coefficients as defined in Equation 23, and perform another run. Steps 2 and 3 will be repeated until a run passes.

4. When a run passes, the software will perform verification runs, keeping the same set coefficients until the required number of consecutive verification runs pass.

5. If a verification run fails, steps 3 through 5 will be repeated until the required number of consecutive verification runs passes, or until it is no longer possible to pass within the predetermined maximum total number of runs.

6. When the required number of consecutive verification runs passes, the current set coefficients will be used for testing.

7. If the required number of consecutive verification runs does not pass within the predetermined maximum number of runs, the dyno will stop the coastdown procedure. The vehicle and dyno should be checked for correct operation.

8. If the dynamometer and the vehicle are both operating correctly, the test procedure should be repeated, including the vehicle preparation described in 6.3. As an alternative, the vehicle coefficients may be averaged utilizing at least three consecutive coastdown runs (not including run 1) to determine the final set coefficients as indicated in steps 5 and 6 of the fixed-run procedure below. Note that these vehicle coefficients will have been obtained with varying set coefficients unlike in the fixed-run procedure, however this should not affect the representative nature of the results.

6.9 Fixed-Run Procedure

The fixed-run road load derivation procedure is to be performed as follows:

1. The dynamometer software will perform the initial “stabilization” coastdown run using set coefficients that represent a best guess for the vehicle. Initial coefficients may be obtained using the method described in 6.4.1.

2. The software will determine the measured coefficients from the stabilization run and subtract these coefficients from the target coefficients. This difference is then added to the set coefficients from the stabilization run to arrive at the set coefficients as defined in Equation 23. These set coefficients are used for the remainder of the procedure.

3. The software will then perform a fixed number, N, of coastdown runs (at least three runs, not including the stabilization run), keeping the same set coefficients for each run.

4. After each run, the software will subtract the set coefficients from the measured coefficients for that run, in order to obtain the vehicle coefficients for that run. These are designated L_{xi}, for i = 1 to N.

5. After the N runs are complete, the N sets of vehicle coefficients are averaged together to produce the final vehicle coefficients. The final set coefficients are then calculated by subtracting the final vehicle coefficients from the target coefficients.

6. As an indication of the run repeatability, the PI Metric (PIM) can be calculated. This calculation is described below and is based on the vehicle coefficients from each of the runs, as well as the target coefficients. If the PIM is greater than 1% (or a value determined by test results at the specific laboratory testing), this may indicate problems with the vehicle or test setup.

6.9.1 Calculation of the PI Metric for the Fixed-Run Procedure

The PIM is intended to be used for quality control and diagnostic purposes, not as a pass-fail criterion. Calculation of the PIM relies on an interpretation of the force coefficients as third-order polynomial coefficients describing power versus speed, instead of as second-order coefficients describing force versus speed. This is physically valid, since power is the product of force and speed. Using generic force coefficients as an example, the associated power can be represented as:

$$\text{Power} = F \cdot V = (C_0 + C_1 \cdot V + C_2 \cdot V^2) \cdot V = C_0 \cdot V + C_1 \cdot V^2 + C_2 \cdot V^3 \quad \text{(Eq. 24)}$$

The third-order relationship does not have a constant term. However, this is physically valid since power is necessarily zero when velocity is zero.

Integrating the power versus speed relationship over the coastdown speed range provides a single value characterizing the relationship. For a coastdown speed range of 15 to 115 km/h, the value of this integral would be calculated as:

$$\mathrm{PI} \equiv \int_{15}^{115} C_0 \cdot V + C_1 \cdot V^2 + C_2 \cdot V^3 \ \mathrm{dV} = \left[\frac{1}{2} C_0 \cdot V^2 + \frac{1}{3} C_1 \cdot V^3 + \frac{1}{4} C_2 \cdot V^4\right]_{15}^{115}$$

$$\mathrm{PI} = \tfrac{1}{2} C_0 \cdot (115^2 - 15^2) + \tfrac{1}{3} C_1 \cdot (115^3 - 15^3) + \tfrac{1}{4} C_2 \cdot (115^4 - 15^4) \quad \text{(Eq. 25)}$$

This integral should be calculated for each set of vehicle coefficients to provide $\mathrm{PI}_{\mathrm{Vehicle\_i}}$, and for the target coefficients to provide $\mathrm{PI}_{\mathrm{Target}}$. The PIM can then be calculated as the standard deviation of the $\mathrm{PI}_{\mathrm{Vehicle\_i}}$ values, expressed as a percentage of $\mathrm{PI}_{\mathrm{Target}}$.

$$\mathrm{std}(\mathrm{PI}_{\mathrm{Vehicle\_i}}) \equiv \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\mathrm{PI}_{\mathrm{Vehicle\_i}} - \overline{\mathrm{PI}_{\mathrm{Vehicle}}}\right]^2} \quad \text{(Eq. 26)}$$

$$\overline{\mathrm{PI}_{\mathrm{Vehicle}}} \equiv \frac{1}{N}\sum_{i=1}^{N} \mathrm{PI}_{\mathrm{Vehicle\_i}} \quad \text{(Eq. 27)}$$

$$\mathrm{PI\ Metric} \equiv \frac{100 \times \mathrm{std}(\mathrm{PI}_{\mathrm{Vehicle\_i}})}{\mathrm{PI}_{\mathrm{Target}}} \quad \text{(Eq. 28)}$$

Practical limits may be determined lab-by-lab.

6.10 Dynamometer Calibration Verification Coastdown

Optionally perform a single unloaded coastdown, as described in 6.2.2, within 15 minutes of completing the road load derivation in order to verify the dynamometer calibration.

6.11 Special Provisions for Testing at 20 °F (-7 °C)

For testing performed at 20 °F (-7 °C), the procedures in this document may be used with the following modifications:

1. The procedures in Section 6 are performed in an environmental test site at 20 °F (-7 °C). The 4-hour soak time prescribed in 6.3.1 should be extended to a minimum of 12 hours. However, if consistent with good engineering judgment, a shorter soak time up to a minimum of 4 hours may be used.

2. Optionally, two consecutive “505” cycles (i.e., the first 505 seconds of the UDDS cycle) may be used to precondition the vehicle in lieu of the two consecutive HWFET cycles specified in 6.6.

6.11.1 Determining Target Coefficients at 20 °F (-7 °C)

For testing performed at 20 °F (-7 °C), set coefficients may be derived using the procedures in this document. Determine road load target coefficients using one of the following methods:

1. Target coefficients may be determined performing coastdown tests or using other methods to characterize road load as described in §1066.305 “Procedures for specifying road load forces for motor vehicles at or below 14000 pounds GVWR” based on vehicle operation at a nominal ambient temperature of 20 °F (-7 °C).

2. If road load target coefficients at a nominal ambient temperature of 20 °F (-7 °C) are not available, multiply each term (i.e., F0, F1, F2) of the 68 to 86 °F road load target coefficients by 1.1, and use these as the 20 °F (-7 °C) target coefficients. The 1.1 multiplier approximates a 10% decrease in coastdown time for the test vehicle at cold temperature.

3. Set coefficients derived at 68 to 86 °F may be used for testing at 20 °F (-7 °C), if consistent with good engineering judgment.

NOTE: For regulatory testing, CFR 40 part 1066, subpart H "Cold Temperature Test Procedures" and §1066.305 "Procedures for specifying road load forces for motor vehicles at or below 14,000 pounds GVWR" define the requirements for cold temperature testing.

6.12 Road Load Derivation Report

Sample reports of road load derivation test results are included in Appendix A. Other formats which include the required information may be used.

7. NOTES

7.1 Conversion Factors

7.1.1 Distance

1 m = 39.370 inches = 3.2808 feet
1 km = 0.62137 mile = 3280.8 feet
1 inch = 25.400 mm = 2.5400 cm = 0.025400 m = 1/12 foot
1 mile = 1609.3 m = 1.6093 km = 5280 feet

7.1.2 Speed

1 km/h = 0.62137 mph = 0.27778 m/s = 0.91134 ft/s
1 mph = 1.6093 km/h = 0.44704 m/s = 1.4667 ft/s

7.1.3 Acceleration

1 (km/h)/s = 0.62137 mph/s = 0.27778 m/s^2 = 0.91134 ft/s^2
1 mph/s = 1.6093 (km/h)/s = 0.44704 m/s^2 = 1.4667 ft/s^2

7.1.4 Mass

1 pound = 0.45359 kg
1 kg = 2.2046 pounds

7.1.5 Force

1 N = 0.22481 pound = 0.029974 HP at 50 mph
1 pound = 4.4482 N = 0.13333 HP at 50 mph

7.1.6 Torque

1 N·m = 0.73756 lb·ft = 8.8507 lb·in
1 lb·ft = 1.3558 N·m = 12 lb·in

7.1.7 Pressure

1 kPa = 0.14504 psi = 0.29530 in Hg = 0.01 bar
1 lb/in^2 = 6.8948 kPa = 2.2036 in Hg = 0.06895 bar

7.1.8 Energy

1 N·m = 0.73756 ft·lb = 1 J = 1 W·s
1 ft·lb = 1.3358 N·M = 1.3558 J