Technical Report

Determination of Tire Energy Dissipation
Analysis and
Recommended Practices

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by

Glenn D. Thompson
Richard N. Burgeson

Notice

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
U.S. Environmental Protection Agency

Abstract

The vehicle tire has a very significant effect on the fuel consumption of the vehicle. For example, during low speed operation the tire is the major source of external energy dissipation by the vehicle. Because of the large effects of the tires and because significant variations have been observed among tires, it is important that the vehicles used for EPA fuel economy measurements be equipped with appropriate tires.

As an initial step to insure test vehicles are equipped with appropriate tires, EPA issued Advisory Circular AC-55A to require tire information for those vehicles for which an alternate dynamometer power absorption was requested. This Advisory Circular stated that requiring such tire information, as type, size, manufacturer, sidewall cord materials, belt material, and the number of sidewall and belt plies was an interim approach until a standardized, acceptable test procedure for determining tire energy dissipation was available.

This report analyzes the currently available methods and test equipment for determining tire energy dissipation. It is concluded that a fully transient procedure is preferred, however such a procedure could not be conducted on equipment in current widespread use. It is however, feasible to conduct thermally transient measurements on free rolling tires with the prevailing equipment. Consequently, a Recommended Practice for the Determination of Tire Energy Dissipation -Quasi Steady State Procedure is provided as Appendix A of this report. In addition, a preferred,

Recommended Practice for Determination of Tire Energy Dissipation - Transient Procedure is provided as Appendix B.

Determination of Tire Energy Dissipation

I. Purpose

This report presents test procedures for the determination of tire energy dissipation information. The determination of tire energy dissipation information will enable more appropriate, realistic testing of vehicles for both exhaust emissions and fuel economy measurements. The decisions made in developing these test procedures for determination of tire energy dissipation are documented in this report.

II. Background

During low speed operation, the tire is the major source of energy dissipation by the vehicle. Consequently, the vehicle tire has a very significant effect on the fuel consumption and emissions (especially oxides of nitrogen) of the vehicle.

A recent experimental effort reported variations in tire rolling resistance with respect to tire type, tire size, and tire manufacturer. (1)* Consequently, to improve exhaust emissions and fuel economy tests, EPA issued Advisory Circular AC 55A to require tire information for those vehicles for which an alternate dynamometer power absorption was requested. This Advisory Circular stated that requesting such tire information as

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* Numbers within parenthesis designate references given at the end of the paper.

type, size, manufacturer, sidewall cord materials, belt material, and the number of sidewall and belt plies, was an interim approach until a standardized, acceptable test procedure for determining tire energy dissipation was available.

III. Discussion

The development of a laboratory test procedure to simulate the "real world" experience of some device always represents compromises between the simulation accuracy and the test expediency. The decisions in these areas must, of course, depend on the purpose the user intends for the resulting information. This section presents the questions which arose during the development of the EPA recommended practices for tire energy dissipation determination and the decisions which were made. The subsequent sections present the actual recommended procedures for tire energy dissipation determination.

A. Applications for Tire Energy Dissipation Information

Tire energy dissipation information is desired for the following reasons:

- Support of the EPA exhaust emission certification and fuel economy measurement programs;

- To provide direction, incentive, and reward for the production of low energy dissipation tires; and

To provide public information and guidance on the fuel economy effects of tire selection.

The information necessary to support the EPA exhaust emission and fuel economy measurements is the most important and immediate need for EPA. During the EPA tests the vehicle tires dissipate approximately 30 percent of the energy delivered to the vehicle wheels. The choice of tires installed on the EPA test vehicles and on the production vehicles is presently virtually uncontrolled.* By comparison, test vehicle inertia simulation and the dynamometer power absorption each have approximately the same effect on the vehicle energy dissipation over the composite of the two cycles as do the vehicle tires. Each of these two parameters, however, is controlled to approximately ± 3 percent.

EPA awareness or control of tire selection for the test vehicles is only important if variations exist among tires. This has been investigated and average differences of approximately 25 percent were observed between tire types. Within tire types, significant variations by manufacturers were observed as were variations by tire size. (2)

The second reason for EPA interest, to provide incentive and reward for the use of low energy dissipation tires is of major importance, but not quite the same immediate concern as the previous reason. This incentive, at least for OEM tires, already exists in the fuel economy standards.

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* Some control does exist over tire selection in the case of vehicles using requested alternate dynamometer power absorptions. However, even this control is based on such parameters as tire type, size, manufacturer, etc., and does not directly consider the tire energy dissipation.

The important aspect is to focus the tire development efforts toward improved tire performance for the consumer.

The third reason, to provide public information and guidance on the fuel economy effects of various tires, is probably the most important long range goal. This area is extremely important for fuel conservation because of the important role of the tire on fuel consumption, and since approximately 80 percent of all tires sold are aftermarket replacement tires. Even with the potential national importance, this goal must be considered as secondary for EPA compared to supporting current programs. The important aspect is to avoid EPA actions or decisions which might compromise this long range objective.

B. Tire Test Approaches

Practices for tire testing range from energy dissipation measurements under steady state free rolling conditions to measurements under conditions which simulate the tire experience on the vehicle. The major difference is that simulation of the tire experience on a vehicle must involve transient conditions and transmitted forces which are not present in the simpler steady state practices. The following chart outlines the transient versus steady state differences.

Steady State	Vehicle Simulation
Warmed up tire	Initially cold tire, tire temperature increases during the test
Constant inflation pressure	Inflation pressure increases as the tire temperature increases
Free rolling tire	Forces transmitted by the tire (driving and braking)
Steady speed	Transient speeds

In addition to the transient versus steady state question, the question of a dynamometer roll or wheel versus a flat surface belt type test machine must be considered. All of these areas will be discussed in the following sections.

1. Initially Cold Tire vs. Warmed Up Tire

Tire energy dissipation significantly decreases as the tire warms up, as shown in Figure 1. (3) This effect occurs for two reasons. As the tire warms up, the temperature of the contained air increases, which results in an increase in inflation pressure and a subsequent decrease in the tire deflection. In addition, the rubber hysteresis decreases with increasing temperature, therefore the energy dissipation for a given deflection also decreases with increasing tire temperature.

Any tire test which attempts to simulate vehicle use must start with a cold tire. Depending on the length of the test period, a temperature transient test procedure may have the advantage of requiring less total test time than measurements on a tire at thermal equilibrium since

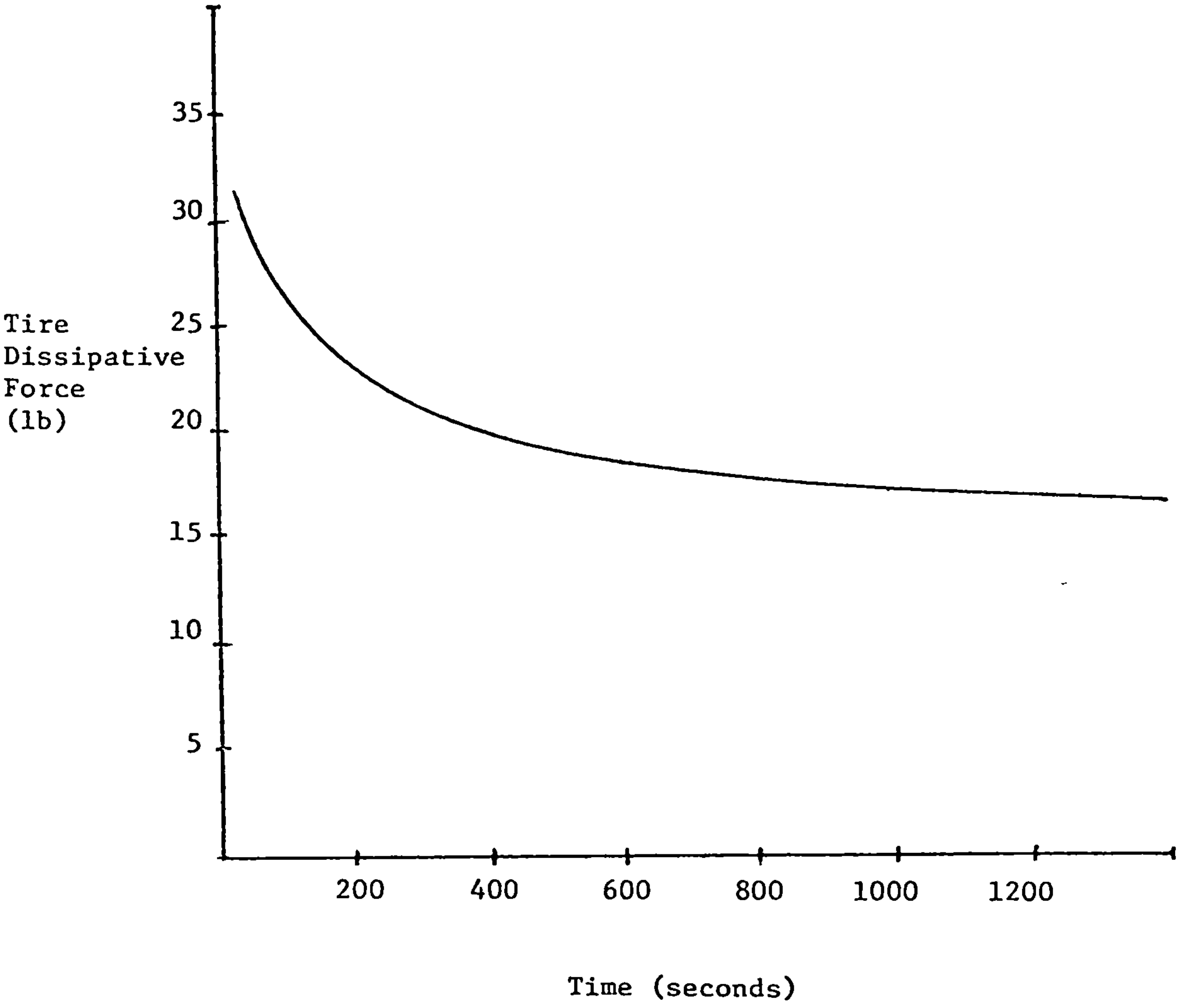


Figure 1 - Typical Tire Energy Dissipation
Force vs. Time

light-duty vehicle tires require approximately 30 minutes to reach thermal equilibrium.

The disadvantage of the thermally transient test is that multiple or continuous data sampling is required during the test. Also, the thermal experience of the tire prior to the test becomes a significant factor in the test results.

The thermally transient cycle is considered preferred for the EPA recommended practice because of the improved simulation of the normal tire experience. For example, considering the data of Figure 1, the tire energy dissipation at thermal equilibrium is about 20 percent lower than the average tire energy dissipation over the first 20 minutes of the tire operation.

2. Inflation Pressure Build vs. Constant Inflation Pressure

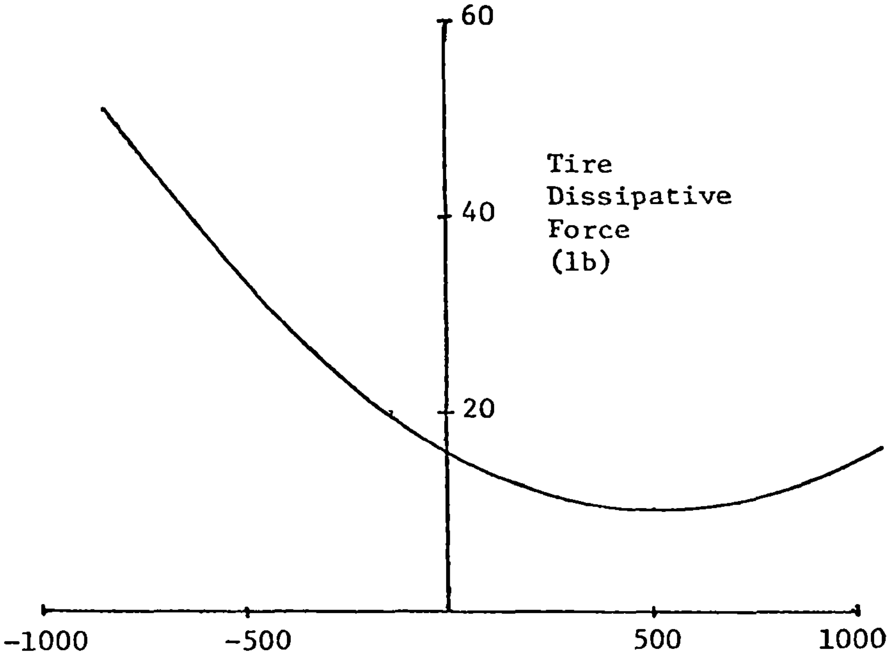
This question is strongly related to the transient temperature question since the temperature effect is primarily a temperature-pressure effect. If simulation of the tire experience on the vehicle is important, then the effects of the inflation pressure increase with increasing temperature must be considered. As in the previous case, no major disadvantages are incurred with a test practice of this nature, therefore this is considered to be the preferred method. Separation of this effect into individual temperature and pressure effects is difficult and is artificial since the separation does not occur during consumer vehicle use.

3. Forces Transmitted by the Tire vs. the Free Rolling Tire

When the tire is used on a vehicle, all tires often transmit negative (braking) forces. In addition, the drive tires must transmit the positive drive forces.

Unfortunately, measuring the tire energy dissipation for a tire under tractive effort is considerably more difficult than measurements on a free rolling tire. This difficulty occurs because the transmitted tractive forces are much greater than the tire energy dissipation forces. In effect two large quantities, the input force and the output force, must both be measured and then subtracted to obtain the small difference which is the tire energy dissipation. For example, the force necessary to maintain a vehicle at a steady 50 mph are typically 100 to 150 pounds at the road-drive tire interface. During accelerations the forces may approach 1000 pounds. By comparison the drive tire dissipation forces would typically be 30 pounds.

Because of the greater difficulty in performing tire energy dissipation measurements on tires transmitting forces, few facilities exist which can conduct such tests. Consequently, there is very little information in the literature on tire energy dissipation during force transmission. However, limited data reported by Calspan for a single tire indicates that tire energy dissipation increases as the tractive effort of the tire increases. (4) A plot of these data is presented in Figure 2. In general, this is to be expected since the tire undergoes greater deformation



Transmitted Longitudinal Force (lb)

Figure 2 - Tire Energy Dissipative Force is Transmitted Force

when transmitting high forces and this deformation must result in greater tire energy dissipation. Consequently, energy dissipation measurements on free rolling tires probably underestimate the on-road tire energy dissipation. In addition, there is reason to believe that tires with different construction parameters, such as ply angle, or different cord materials, may behave differently when transmitting force. (5)

In general, measurements of tire energy dissipation when the tire is transmitting force would be the preferred test method. However, at the present time this is not considered practical for most test facilities.

4. Transient Speed vs. Steady Speed

In typical consumer use, vehicle tires are operated in speed transient modes. Therefore, from the vehicle simulation standpoint, a speed transient test is desired. The forces responsible for tire energy dissipation are, however, relatively speed independent, at least for moderate speeds. (6) Therefore, there is reduced need for a speed transient cycle to consider direct speed induced effects on the tire rolling resistance. The tire power dissipation however does increase with speed since the power is the product of the force and velocity. Therefore the rate of energy dissipation and the rate at which heat is generated in the tire does increase with vehicle speed. Consequently, the thermal experience of the tire may be speed dependent even if the forces are not.

The speed transient experience of tires in consumer use is primarily important because the drive tires are the vehicle mechanism for generating the transient vehicle speeds and this requires the tires to transmit large forces. Consequently, for a tire test procedure, a speed transient cycle is primarily important if this is used as a method of requiring the tire to transmit large forces. Therefore, the question of a speed transient cycle for a tire test is really the same as the previous question of tire force transmission.

A speed transient test, with mechanical inertia simulation, does have some advantages as an approach for generating transmitted forces. The primary advantage is that the inertia system is basically energy "conservative". That is, energy supplied by the tire to accelerate the flywheels will be returned to the tire during deceleration. Consequently only the net energy supplied to the tire must be measured and the load forces supplied to the test machine by the inertia simulation need not be monitored. In effect the flywheel approach eliminates the need to measure two large quantities and compute a difference. Consequently only one transducer need be calibrated with great precision. Even here some reduction in transducer precision may be tolerable as long as the response is symmetric in traction and braking. The only disadvantage is that the flywheel bearing losses must be known to compensate for the measured energy dissipation.

The mechanical flywheel, speed transient approach is the preferred approach since this method requires the tire to transmit tractive force, correctly simulates the rate of energy dissipation during consumer use and appears to have potential test machine advantages.

5. Flat Bed vs. Dynamometer Wheel

The final question is the advantages of a flat bed test machine versus a cylindrical test wheel.

The flat bed has the obvious advantage of being the logical equivalent of the road surface. There are also significant engineering advantages to a flat belt test machine. The major advantage is that the tire energy dissipation is different on a flat surface versus a cylindrical surface. Consequently, correction factors must be used to compare data from curved surface test machines to flat surface results. (7) Also, conversion factors must be used to compare data from curved surface machines of different diameters or even to compare curved surface data collected by different types of transducers, i.e., torque versus force sensors. These correction factors are, on the average, reasonably accurate for a large collection of tires. However, they may not be precisely accurate for any given tire. Consequently, tires may rank differently for different cylindrical surface test machines. Conversely, however, all flat bed machines should, at least, rank tires in the same order.

The disadvantages of a flat bed machine are their cost and availability. Only one such device, the Calspan facility, is currently commercially active. A smaller flat bed test facility, the prototype for the Calspan machine, exists at the University of Pennsylvania. In addition, General Motors has a flat bed tire test facility currently under construction.

Even though the flat bed approach is the preferred method, the limited availability of these test machines precludes extensive use of this type of tire test apparatus in the near future.

IV. Conclusions

The preferred tire test procedure should be thermally transient, require the tire to transmit torque, and should be conducted on a flat test surface. However, wide usage of such a procedure is not practical at the current time because of test facility limitations.

Since EPA has a definite, immediate need for tire energy dissipation information,a recommended practice for obtaining this information on available facilities is necessary. The capability limitations of those facilities which are widely available at this time preclude measurements on tires which are transmitting force. Therefore a simpler procedure which can be performed in the majority of the existing facilities should be considered. This procedure should be a thermally transient, steady state speed measurement of free rolling tire energy dissipation on a cylindrical test machine. It is concluded that such an approach can yield useful information, at least, when comparing tires tested at one facility. A recommended practice of this nature is presented as Appendix A of this report.

It is also concluded that there are potential problems in any procedure which only considers free rolling tires on a cylindrical surface. For this reason data collection by more preferred procedures should be encouraged. Consequently, a recommended practice for determination of tire energy dissipation when the tires are transmitting forces to a flat surface should be provided for eventual use. This fully transient test procedure is presented as Appendix B of this report.

References

1. G.D. Thompson and M. Torres, "Variations in Tire Rolling Resistance" EPA Technical Support Report for Regulatory Action. October 1977.

2. IBID

3. D.J. Schuring, "Rolling Resistance of Tire Measured Under Transient and Equilibrium Conditions on Calspans Tire Research Facility", Final Report to U.S. Department of Transportation, Office of Systems Development and Technology under Contract DOT-TSC-OST-76-9, March 1976.

4. IBID

5. I. Gusakov, telephone conversation.

6. G.D. Thompson, "Light-Duty Vehicle Road Load Determination", EPA Technical Support Report for Regulatory Action, April 1977.

7. S.K. Clark, "Rolling Resistance Forces in Pneumatic Tires", Interim Report prepared for the U.S. Department of Transportation, Transporation Systems Center under Contract DOT-TSC-1031, January 1976.

Appendix A

Recommended Practice for Determination of Tire Energy Dissipation - Quasi Steady State Procedure

This recommended practice provides a procedure to determine tire energy dissipation for a free rolling tire at primarily steady state speed but considering the thermally transient nature of the energy dissipation during the tire warm up.

A. Test Dynamometer Requirements

The test dynamometer shall be a large diameter (greater than 1 m) cylindrical surface machine. The test machine shall be capable of supplying a force on the tire perpendicular to the test surface and be able to measure the torques required to rotate the tire. During this process the machine must be capable of maintaining a constant speed, and capable of measuring this speed and the peripheral distance traveled by the test surface.

1. Vertical force - The test machine shall be capable of imposing constant forces between 2000 nt and 8000 nt on the tire perpendicular to the test surface. The machine shall be capable of maintaining the load on tire constant to within ± 40 nt and shall be capable of measuring this load to within ± 10 nt.

2. Tire Dissipation Forces - The test machine shall be capable of measuring the torques required to rotate the test tire to within ± 2 nt-m (1 ft-lb).

3. Test Speed - The machine shall be capable of maintaining the desired test speed to within ± 1 m/sec (2 mi/hr) and shall be capable of measuring

this speed to within ± 0.1 m/sec. (0.2 mi/hr)

4. Loaded Radius - The test machine shall have a method of measuring the loaded radius of the tire; that is, the perpendicular distance from the axis of rotation of the tire to the test surface. This distance measurement shall be accurate to within ± 1 mm (± 0.05 in.)

5. The Test Surface - The test surface of the machine shall be a bonded abrasive aggregate of approximately number 80 grit.

B. The Test Cell Requirements

The requirements for the test cell, is that the ambient temperature be well controlled. In addition, the support services of compressed air should be available for tire inflation as should the necessary gauges to measure tire inflation.

1. Temperature - The temperature in the test cell and in any area used to store the tire within four hours prior to testing shall be maintained at 20°C ± 2°C (68°F ± 4°F).

2. Tire Inflation Pressure Gauges - The gauges used to measure the tire inflation pressures shall be accurate to within ± 0.5 kPaG (± 0.07 psi).

C. Test Procedure

The test procedure consists of the following steps:

- Tire break-in
- Equilibration of the tire to the test ambient temperature
- Installation of the tire on the test machine
- Operation of the tire over the test cycle

1. Tire Break-In - The test tires shall be mounted on appropriate rims and shall be operated for a minimum of 100 km and a maximum of 500 km prior to testing. An appropriate rim is one of an approved contour and width as specified for the test tire in the current yearbook of the Tire and Rim Association Inc. The tire break-in may be conducted with a vehicle on a road or track surface, or may be accumulated on the tire test machine. During the break-in period, the compressive load on the tire shall be at least 80% of the maximum design load of the tire.

2. Equilibration to the Test Temperature - After tire break-in the tire shall be stored in an environment of 20°C ± 2°C for a minimum of four hours preceeding the test. During this period the tire inflation pressure should be checked and adjusted if necessary to the cold inflation pressure for the test. The test inflation pressures shall be the appropriate design cold inflation pressures specified in the current

Yearbook of the Tire and Rim Association Inc. for the tire size and load. Any adjustment of the inflation pressure should occur approximately one hour before the test period to provide adequate time for any air introduced into the tire to reach the equilibrium temperature.

3. Installation on the Test Machine - The tire shall be installed on the test machine and the load on the tire perpendicular to the test surface shall be adjusted to 80% of the maximum design load of the tire, for the test pressure. The alignment of the loaded tire shall be:

- Perpendicular to the test surface ± 1°

- Slip angle 0 ± 0.25°

- Camber angle 0° ± 0.50°

At this time the inflation pressure of the tire shall be checked and recorded. The tire inflation pressure may be adjusted, up to a maximum adjustment of 10 kPa (1.5 psi) at this time. Tire inflation shall be correct to within ± 1 kPa (0.15 psi)

4. Operation Over the Test Cycles - The test machine shall be accelerated from rest to the test speed of 10 m/sec at the approximate rate of 1 m/sec^2. The test speed of 10 m/sec shall be maintained for 1,200 seconds (20 min.), after which the tire shall be brought to a stop with a deceleration rate of approximately 1 m/sec^2. A graphical representation of this test cycle is given in the attachment of this appendix.

The tire shall then be allowed to remain at rest on the test machine for 600 seconds (10 minutes).

After completion of the 10 minute stationary phase the tire shall be accelerated from rest to a speed of 20 m/sec at the rate of 1 m/sec^2. The test speed of 20 m/sec shall be maintained for 800 seconds (13.33 minutes) after which the tire shall be brought to a stop with a deceleration rate of 1 m/sec. A graphical representation of this test cycle is included in the attachment of this Appendix.

During all steady speed test phases the torques necessary to rotate the tire and the velocities of the test surface shall be measured. These data shall be recorded, preferably each second, but a minimum frequency of once every five seconds is acceptable.

D. Data Analysis

The data analysis consists of three steps, computation of the total energy required for each cycle, subtraction of the energy dissipation from the residual friction of the test machine to determine the net tire energy dissipation and finally the computation of an energy dissipation coefficient.

1. Computation of the Total Energy Dissipation - The torque necessary to drive the tire shall be multiplied by the angular velocity of this shaft transmitting the drive torque to determine the instantaneous power. That is:

$$P_i = T_i \omega_i$$

where: P_i = the power dissipated during the i^{th} time interval

T_i = the torque measured during the i^{th} time interval

ω_i = the angular velocity during the i^{th} time interval

The instantaneous powers shall then be multiplied by the sample time period and summed to give the total energy dissipation over each test cycle:

$$E_s = \sum_i p_i t_i$$

where:

E_s = the total system energy dissipation

t_i = the length of the i^{th} time interval

2. The Tire Energy Dissipation - The tire energy dissipation shall be calculated from the total system energy by subtraction of the energy dissipation caused by the mechanical friction of the system. That is:

$$E_t = E_s - E_f$$

where:

E_t = the tire energy dissipation

E_f = the energy dissipation caused by friction in the test machine during the test cycle.

The methods used to determine E_f will depend on the specific design of the test machine. The quantity E_f should, of course, only include those friction losses which were included in the measurement of E_s. If the quanity E_f varies with time during the test cycle this variation must be considered.

A specific energy dissipation coefficient can now be computed from the tire energy dissipation of each cycle by dividing this quantity by the total distance the test surface traveled and by the load on the tire perpendicular to this surface.

$$e = E_t/LD$$

where:

e = specific energy dissipation coefficient
L = the load on the tire normal to the test surface
D = the distance traveled by the test surface

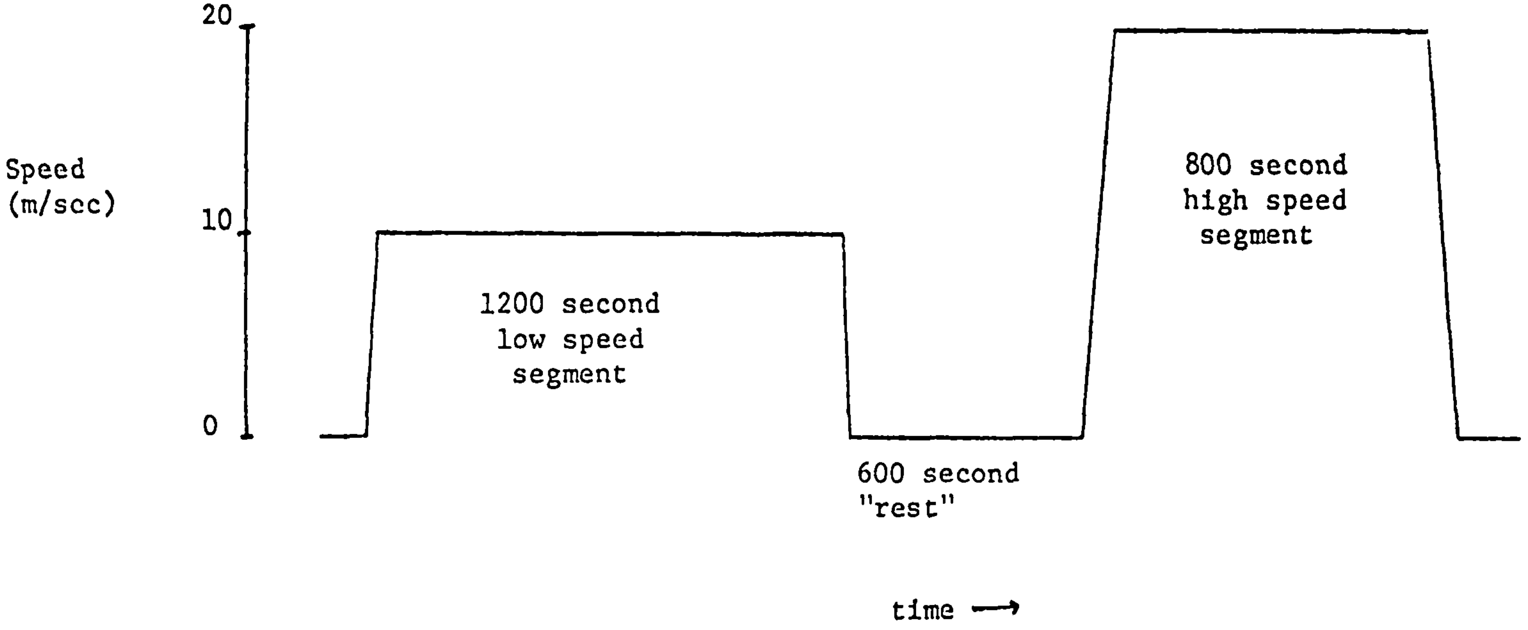
It should be noted that e is a dimensionless coefficient and is equivalent to the average rolling resistance coefficient over the test cycle.

Attachment

to

Appendix A

Graphical Representation of the Quasi Steady State Cycles



Graphical Representation of
the Quasi - Steady State Cycles

Appendix B

Recommended Practice for Determination of Tire Energy Dissipation - Transient Procedure

This recommended practice provides a procedure to determine tire energy dissipation under transient conditions. This recommended practice closely simulates the tire experience on consumer vehicles. Consequently it considers both driving tires exerting tractive forces and non-driving or free rolling tires. The EPA driving cycles are chosen as test cycles representative of consumer vehicle use.

A. Test Dynamometer Requirements

The tire test machine (dynamometer) should be a flat belt machine which can accommodate two tires, one tire representing the vehicle driving tire and one representing the non-driving tire. Each tire shall receive a force normal to the test surface which is equivalent to 80% of its load rating. The system should be driven by driving one tire, the "driving tire" such that the peripheral velocity of the test surface corresponds to the EPA driving schedules. Graphical plots and speed versus time listings for each of the driving schedules are provided as an attachment to this recommended practice. The torque or force requirement of the driving tire shall be measured during each second of the driving schedules. The tire forces and the instantaneous velocity of the test surface shall be recorded throughout the cycle.

1. Vertical force - The test machine shall be capable of imposing constant forces between 2000 nt and 8000 nt on the tire perpendicular to the test surface. The machine shall be capable of maintaining the load on tire constant to within ± 40 nt and shall be capable of measuring this load to ± 10 nt.

2. Tire Dissipation Forces - The test machine shall be capable of measuring the forces required to drive the test tire to within ± 1 nt.

3. Test Speed - The machine shall be capable of maintaining the desired test schedule speed to within ± 1 m/sec (2 mi/hr) and shall be capable of measuring this speed to within ± 0.1 m/sec. (0.2 mi/hr)

4. Inertia Simulation - The tire test dynamometer shall be adjusted to apply an inertia simulation appropriate for a vehicle with a mass equivalent to the total normal load upon the test tires. That is, of the available increments of simulated inertial mass, that simulated inertia which is nearest to the total normal load force on the tires divided by the gravitational constant ($9.80 m/sec^2$) shall be selected.

The inertia increments shall be 50 kg or less and the accuracy of the inertial simulation shall be within ± 1 kg of the selected inertia.

5. Loaded Radius - The test machine shall have a method of measuring the loaded radius of the tire; that is, the perpendicular distance from the axis of rotation of the tire to the test surface. This distance measurement shall be accurate to within ± 1 mm (± 0.05 in.)

6. The Test Surface - The test surface of the machine shall be a bonded abrasive aggregate of approximately number 80 grit.

B. The Test Cell Requirements

The requirements for the test cell, is that the ambient temperature be well controlled. In addition, the support services of compressed air should be available for tire inflation as should and the necessary gauges to measure tire inflation.

1. Temperature - The temperature in the test cell and in any area used to store the tire within four hours prior to testing shall be maintained at 20°C ± 2°C (68°F ± 4°F).

2. Tire Inflation Pressure Gauges - The gauges used to measure the tire inflation pressures shall be accurate to with ± 0.5 kPa (0.07 psi).

C. Test Procedure

The test procedure consists of the following steps:

- Tire break-in

- Equilibration of the tire to the test ambient temperature

- Installation of the tire on the test machine

- Operation of the tire over the test cycle

1. Tire Break-In - The test tires shall be mounted on appropriate rims and shall be operated for a minimum of 100 km and a maximum of 500 km prior to testing. An appropriate rim is one of an approved contour and width as specified for the test tire in the current yearbook of the Tire and Rim Association, Inc. The tire break-in many be conducted with a vehicle on a road or track surface, or may be accumulated on the tire test machine. During the break-in period, the vertical load on the tire shall be at least 80% of the maximum design load of the tire.

2. Equilibration to the Test Temperature - After tire break-in the tire shall be stored in an environment of 20°C ± 2°C for a minimum of four hours preceeding the test. During this period the tire inflation pressure should be checked and adjusted if necessary to the cold inflation pressure for the test. The test inflation pressures shall be the appropriate design cold inflation pressure specified in the current Yearbook of the Tire and Rim Association, Inc. for the test tire size and load. Any adjustment of the inflation pressure should occur prior to the last hour of the temperature equilibration period to provide adequate time for any air introduced into the tire to reach the equilibrium temperature.

3. Installation on the Test Machine - The tire shall be installed on the test machine and the load on the tire perpendicular to the test surface shall be adjusted to 80% of the maximum design load of the tire. The alignment of the loaded tire shall be:

Perpendicular to the test surface ± 0.30°

- Slip angle 0 ± 0.25°

- Camber angle 0° ± 0.50°

At this time the inflation pressure of the tire shall be finally checked and recorded. The tire inflation pressure may be adjusted up to a maximum of 10 kPa (1.5 psi) at this time. Tire inflation pressure shall be correct to within ± 1 kPa (0.15 psi)

4. Operation Over the Test Cycles -

   a. The tires shall be operated over the cold transient portion of the EPA urban driving schedule (the first 505 seconds).

   b. The tire shall be operated over the hot stabilized portion of the EPA urban driving schedule (from the 505 to the 1371 second points).

   c. The tires shall be allowed to "rest" on the test machine for 10 minutes and then the first 505 seconds of the EPA urban cycle shall be repeated. This is the hot transient segment of the test.

   d. After completion of the second 505 seconds of the EPA urban cycle the tires shall be immediately operated over the EPA Highway Fuel Economy Cycle.

During all dynamic test phases the force necessary to drive the tire shall be monitored as shall the velocities of the test surface. These data shall be recorded, each second.

D. Data Analysis

The data analysis consists of three steps, computation of the total energy required for each cyle, substraction of the energy dissipation from the residual friction of the test machine to determine the net tire energy dissipation and finally the computation of an energy dissipation coefficient.

1. Computation of the Total Energy Dissipation - The force necessary to drive the tire shall be multiplied by the test surface velocity to determine the instantaneous power. This is:

$$p_i = f_i v_i$$

where:

p_i = the power required during the i^{th} interval

f_i = the force measured during the i^{th} interval

v_i = the velocity of the i^{th} interval

The instantaneous powers shall then be multiplied by the sample time period and summed to give the total energy dissipation over each test cycle:

$$E_s = \sum_i p_i t_i$$

where:

E_s = the total system energy dissipation

t_i = the length of the i^{th} time interval

2. The Tire Energy Dissipation - The tire energy dissipation shall be calculated from the total system energy by subtraction of the energy dissipation caused by the mechanical friction of the system. That is:

$$E_t = E_s - E_f$$

where:

E_t = the tire energy dissipation

E_f = the energy dissipation caused by friction in the test machine during the test cycle.

The methods used to determine E_f will depend on the specific design of the test machine. The quantity E_f should, of course, only include those friction losses which were included in the measurement of E_s. If the quantity E_f varies with time during the test cycle, this variation must be considered.

A weighted average energy dissipation coefficient can now be computed for the urban cycle by dividing the total tire energy dissipation by the total distance the test surface traveled and by the total load on the tires perpendicular to this surface.

$$e_u = 0.43 \quad [(E_{ct} + E_{st})/(D_{ct} + D_{st})L]$$

$$+ 0.57 \quad [(E_{ht} + E_{st})/(D_{ht} + D_{st})L]$$

where:

e_u = specific energy dissipation coefficent for the urban cycle

E_{ct} = the tire energy dissipated over the initial segment of the urban test cycle (4a)

E_{st} = the tire energy dissipated over the second test segment of the urban cycle (4b)

D_{ct} = the distance traveled during the initial segment of the urban test cycle (4d)

D_{st} = the distance traveled during the second segment of the urban cycle. (4b)

L = the total load on both tires normal to the test surface

E_{ht} = the tire energy dissipated over the repeat of the first urban test segment (4c)

D_{ht} = the distance traveled over the repeat of the first urban test segment (4c)

0.43 and 0.57 are the weighting factors representing 43 percent of all urban trips as starting with initially cold tires and 57 percent of urban trips starting with warm tires.

It should be noted that e_u is a dimensionless coefficient and is equivalent to the average rolling resistance coefficient over the urban test cycle.

An average energy dissipation coefficient can be computed for the highway cycle in a similar, but simpler manner. This energy dissipation coefficient is:

$$e_h = E_{hw}/D_{hw}L$$

where:

e_h = the energy dissipation coefficient for the highway cycle

E_{hw} = the energy dissipation over the EPA highway cycle

D_{hw} = the distance traveled over the highway cycle

L = the total load on both tires normal to the test surface

The energy dissipation coefficients for the two cycles can be harmonically averaged to yield a composite energy dissipation coefficient. The composite energy dissipation coefficient is given by:

$$e_c = \frac{1}{\frac{0.55}{e_a} + \frac{0.45}{e_h}}$$

where:

e_c = the composite energy dissipation coefficient

0.55 and 0.45 are the weighting factors based on 55 percent of all mileage represented by the urban cycle and 45 percent of all mileage represented by the highway cycle.

Attachment to

APPENDIX B

EPA Urban and Highway Fuel Economy Driving Schedules