SDSB 79-06

Technical Report

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Summary and Analysis of Comments Received in Response to the EPA Report

Determination of Tire Energy Dissipation Analysis and Recommended Practices

by

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NOTICE

Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

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

I. Introduction

This document presents, summarizes and analyzes the comments received in response to the EPA Draft Report, "Determination of Tire Energy Dissipation-Analysis and Recommended Practices". These comments were solicited by distributing the Draft Report at the April 26 meeting of the SAE Tire Rolling Resistance Subcommittee and by distribution of the report to MVMA, JAMA, and AIAA.

The distributed EPA report contained two recommended practices for determination of tire energy dissipation. The first recommended practice determined the tire energy dissipation by driving an initially cold tire at steady speeds. As the tire approaches thermal equilibrium, the force required to drive the tire decreases; therefore, this procedure primarily considers the thermal transient behavior of the tire. This procedure is consequently described as either the quasi-steady state procedure or the thermally transient procedure. It is characterized by steady state speeds and slow variations in the measured forces.

The second recommended practice determined the tire energy dissipation as the tire was operated over the transient speed-time cycles used for the EPA exhaust emission certification tests. In this practice, the speed of the tire, the force required to drive the tire, and the thermal characteristics of the tire are all transient. Consequently, this procedure is referred to as the force transient procedure, or simply as the transient procedure.

The subsequent comments and the analysis of these comments are divided according to the recommended practice which was addressed. That is, either the full transient procedure or the simpler thermally transient procedure. In the first section of this report, a synopsis of the comments received from each commentor is presented. These comments are subdivided according to the major topics addressed. In the second section, the summary of comments, a summary of the comments received in each major topic is presented. The analysis section discusses and analyzes the summarized comments. The final section recommends courses of action in each of the areas.

Copies of the original comments, as received, are attached, as is a copy of the material distributed for solicitation of comments. Therefore, this document provides a complete record of the EPA and industry interaction in this important area.

II. Comments

Comments were received from Ford, Firestone, GM, MVMA and SAE. These comments addressed the feasibility of the proposed thermally transient test procedure, the feasibility of the proposed force transient test procedure, the desirability of either procedure, and recommendations suggested by the commentors.

A. Comments on the Practicality of the Proposed Temperature Transient Procedure

Ford:

"The data handling equipment required for the procedure defined in Appendix A (Temperature Transient) is generally not available on tire test machines."

Firestone:

"No test equipment capable of running either of the proposed EPA test procedures is currently available. Design and procurement of such equipment seems unnecessary unless an improvement in results obtained is likely."

"The proposed quasi-steady state test would require precise speed control, increased power to drive the test drum, rapid data sampling at fixed time intervals and software for data processing. Such equipment and software would have to be newly developed or acquired."

B. Comments on the Practicality of the Proposed Force Transient Procedure

GM:

"The energy dissipation factor would be expected to have significant variability since it is determined from the difference between two large numbers."

MVMA:

"It (the recommended transient practice) would also be expected to have little resolution capability since it is derived from the difference of two large numbers, both of which are subject to test variability".

Ford:

"The tire machine required for the procedure defined in Appendix B (Force Transient) does not exist. The highly regarded and very elaborate Calspan flat belt tire machine does not have the capability to run this procedure".

Firestone:

"To obtain necessary precision in the proposed EPA transient test, large horizontal forces must be measured and subtracted from one another with a precision of less than one pound. This is very difficult, if not impossible, to obtain with any available measurement instruments".

C. Comments on the Desirability of Either EPA Test Procedure

GM:

"The preferred test, which incorporates both the driven and undriven wheel in combination with the EPA city and highway cycles would require very expensive equipment and would be very time consuming to conduct. There is no evidence that a test of this complexity is technically justified at this time".

"This would be an additional test for industry since it does not have the general utility needed by vehicle designers to accurately assess effects of design related parameters (load and pressure)".

"The data resulting from such a test methodology seems to center around the anticipated needs of the EPA and would be of little value to industry for the tire and vehicle design process. As pointed out, the current methods routinely used for assessing rolling resistance seem to be satisfactory for at least obtaining major design improvements in tire rolling resistance performance".

Ford:

"The EPA procedure looks at the tire at only one load/tire pressure point. To adequately evaluate a tire, a range of expected load and pressure conditions must be evaluated. If a range of pressures and loads were evaluated, the proposed EPA test procedure would be very time consuming."

MVMA:

"This recommended method would be of little value to industry since it is too specific in nature (only one test load and inflation pressure)."

Firestone:

"The EPA proposed quasi-steady state procedure requires about 45 minutes for each data point and therefore would require at least 225 minutes to provide the five data points covering three loads and three pressures to produce the data provided by the currently proposed SAE procedure which obtains the same tire data in just 70 minutes to test time."

"Any test of a product or machine operating in a transient condition is inherently likely to prove less repeatable than a test run with the product or machine in equilibrium condition."

D. Industry Recommendations

SAE (letter from SAE Subcommitte Chairman, Tom Baker, of UniRoyal) - "I am disturbed by the fact that the report implies that existing test methods are unacceptable and that new ones must be developed. Yet there is no evidence that existing methods, especially the SAE one that Glenn helped us develop, have even been tried by the EPA. How then have they been found unacceptable? If there is evidence to that effect, why has Glenn not brought it to our attention so that we could improve our SAE approach? None of us on the Subcommittee wants a method which does not produce meaningful results."

"It seems to me that the credibility of the information provided is of paramount importance. The credibility of the data is enhanced by the adoption of a standardized test procedure which has the public endorsement of the technical community known to be knowledgeable on the subject. Therefore for the good of the EPA program and for the greater probability of its public acceptance and success, I recommend that the EPA adopt the tried and proven technology of the SAE Recommended Practice rather than attempt to invent new tests. I believe the EPA objective will be well served by the SAE test and we will all be satisfied with the result".

GM:

". . . General Motors recommends that a carefully structured experiment be conducted to demonstrate the effectiveness of each procedure to properly rank order a wide range of tires for their effect on fuel economy. A carefully controlled series of fuel economy tests having repeated measurements on different road schedules and the two EPA laboratory cycles can then be used to confirm the fuel economy-tire energy dissipation/rolling resistance relationship. Analysis of these data will indicate the degree of deficiency that may result from the more simplified current industry practices for evaluating tire performance".

MVMA:

"Before any recommended procedure is adopted, the EPA should conduct a program to demonstrate that the test method has the ability to properly rank order a wide range of tires for their effect on fuel economy. This should then be confirmed by a carefully controlled series of road and laboratory fuel economy tests having a suitable number of repeat measurements. This same group of tires should also be quantified using the current industry practices which incorporate steady-state rolling resistance and accurately measured vehicle fuel economy could then be assessed".

Ford:

"It is suggested that the proposed SAE procedure with monitoring of rolling resistance during warm-up be used for EPA's needs so that tire rolling resistance in non-thermal and thermal equilibrium conditions can be determined".

Firestone:

"We do have data available that show measurements which correlate directly with flat surface measurements can be made on a drum as small as 62.7 inches in diameter but we are not at all sure how far we can go before drum curvature effects become significant. Further research is required on this point, but for now we believe that a minimum test drum diameter of 1.50 meters should be specified".

"Basically, there are known problems with the transient or quasi-steady state test procedures and it seems logical that we should take on these problems only if the transient tests have been proven to give tire values which are either more repeatable or bear a more direct correlation to actual in-use values than steady-state measurements. Neither of these proofs exists".

"The fact that the cycle of operation proposed by EPA represents some particular mode of consumer vehicle operation is not significant with respect to either the question of repeatability or correlation".

III. Summary of Comments

The following summary of comments is presented in the same subject categories as were used for the presentation of the comments.

A. Practicality of the Proposed Temperature Transient Procedure.

Few comments were received on the feasibility of the proposed thermally transient procedure. The two comments which were received stated that equipment commonly available at the present time would not be adequate for this procedure. Both commentors on this aspect specifically mentioned the data acquisition and processing requirements of this proposed procedure.

B. Practicality of the Proposed Force Transient Procedure

Many commentors noted that the proposed force transient procedure would require the measurement and subtraction of the two relatively large forces; the force into the tire, and the force transmitted by the tire, to determine the residual dissipated force. Since the desired quantity is the difference of two larger quantities, most commentors noted that it is subject to greater variability than the determination of the rolling resistance of a free-rolling tire under steady-state conditions.

One commentor also noted that they did not believe that any existing tire test machine was capable of running this procedure.

C. Desirability of Either EPA Test Procedure

The comments received were of the following types.

1. The procedure is more complex than a steady state procedure and is therefore not desirable.

2. The procedure does not address the effects of load and pressure and is therefore inadequate for the tire industry. If these effects are investigated within the current procedure, the test time required is excessive.

D. Industry Recommendations

The majority of the recommendations received from the commentors can be summarized as:

1. An extensive test program should be conducted to insure the results of the proposed EPA test procedures are indicative of the in-use effects of various tires.

2. The draft SAE Recommended Practice for determining tire rolling resistance should be adopted until the results of the above recommended test program are available. One commentor did recommend that the SAE procedure be modified to include data collection during the period of tire warm-up.

In addition to the above general comments, one specific comment was received, that the minimum roll diameter be specified as 1.5m rather than the 1.0m currently in the EPA procedure.

IV. Analysis of Comments

A. Practicality of the Temperature Transient Procedure

No commentors questioned the feasibility of the temperature transient procedure; therefore, it is concluded that all commentors considered the proposed procedure physically feasible. Several commentors did, however, express beliefs that the commonly available tire test equipment is not sufficient for this procedure. Insufficient drive motors, inaccurate speed controls, and lack of the data acquisition equipment required by the procedure were all mentioned. The question about drive motor size and control are somewhat surprising since the proposed procedure does not demand any higher speeds than current industry procedures. If the equipment is satisfactory for current industry procedures, then it should also be satisfactory for the EPA proposed procedure. The only possible exception is the initial acceleration required by the EPA procedure. If this is a problem, the acceleration rate could be decreased to at least reduce the problem.

A potential problem stated by several commentors was that the data acquisition equipment required by the proposed EPA procedure was not commonly available on most current tire test machines. Data acquisition equipment which would be adequate for the proposed test procedure has recently been both purchased and rented by EPA. This equipment is generally available as standard, "off the shelf" hardware, costing approximately $5 to $10K. This reviewer, therefore, concludes that the possible current lack of this equipment does not pose a major problem with the feasibility of the procedure. One tire manufacturer and one automobile manufacturer have both recently offered to conduct tire energy dissipation measurements using this proposed EPA procedure. These offers support the conclusion that the proposed procedure is generally feasible with much of the current equipment or with minor modifications to this equipment.

B. Practicality of the Force Transient Procedure

Several commentors remarked that the force transient procedure was impractical because the desired parameter, the tire energy dissipation, is determined by the subtraction of the force transmitted by the tire from the energy transmitted to the tire, both quantities being larger than the subsequent difference. Several commentors stated that they did not believe this procedure could be performed on any existing tire test machine.

It is an intrinsic aspect of the force transient procedure that the tire is required to transmit force. Consequently, the problem of monitoring a small force in the presence of larger forces cannot be avoided. This is, of course, more difficult than a steady state or quasi-steady state measurement conditions. This does not, however, mean that the procedure is not feasible.

EPA recently advertised a contract to obtain tire energy dissipation measurements using this force transient procedure. All proposers for the contract believed the approach was feasible. The results of this contract, which was awarded to the Pennsylvania Transportation Institute, will demonstrate the degree of practicality of this method. All prospective contractors which responded to the EPA request for proposals did anticipate modifications to existing equipment or construction of new test machines. This does support the comments that existing equipment would require modifications or replacement to conduct this test procedure.

C. Desirability of the Proposed EPA Procedures

The commentors presented two major points in regard to the proposed EPA procedures. With respect to the force transient procedure the comment was made that this procedure would require expensive equipment, and that there was no evidence that such a complex test procedure was technically justified. This comment is technically correct since few, if any tire tests have been conducted using the force transient procedure. It does however ignore some available literature data which indicate that tires may behave differently in force transient conditions and that a procedure which includes these conditions may be necessary to accurately reflect the consumer use of the tire. (1)

It has consistently been the position of EPA that the expense and complexity of the proposed force transient test should be incurred only if this test is necessary to accurately simulate the experience of the

(1) D.J. Schuring, "Rolling Resistance of Tires Measured Under Transient and Equilibrium Conditions on Calspan's Tire Research Facility. DOT-TSC-OST-76-9, March 1976.

tire in consumer use. Since these data are currently not available, but should soon be developed as a result of a current EPA contract, it is concluded that the decision about the necessity of a force transient procedure be postponed until the results from the current EPA contract are available.

Several commentors expressed the opinion that neither of the EPA proposed test procedures were desirable since they did not address such design parameters as load and pressure. These parameters were not considered in the EPA practice since they are considered to be of primary interest to the vehicle designer and only of secondary interest to the EPA question of the tire energy dissipation. While the EPA proposed test does not provide this sensitivity information, it is not in any direct conflict with procedures to determine these quantities.

D. Recommendations Received from the Industry

The most prevalent comment received was that EPA should adopt the current draft SAE procedure. This simpler procedure only considers the energy dissipation of a tire with regulated inflation pressure when operated in thermal equilibrium at a steady speed of 50 mph. The following comment was typical of those received:

"Basically, there are known problems with the transient or quasi-steady state test procedures and it seems logical that we should take on these problems only if the transient tests have been proven to give tire values which are either more repeatable or bear a more direct correlation to actual in-use values than steady-state measurements. Neither of these proofs exists".

Yet the same authors of this comment, D.J. Schuring et al, responded to the draft SAE procedure with a letter stating:

"The fundamental purpose of an SAE test procedure surely must be to assess the performance of like products with respect to some aspect of interest. The end result of running such tests must be to compare products one with another so a choice between them can be made or so that the uniformity of their performance can be evaluated".

"Particularly in this case, we need a test procedure which can be used to measure the new ideas and products which are being developed and will be developed over the next few years as part of our high-priority search for ways to reduce fuel consumption of automobiles".

"The proposed (SAE) test procedure provides the pressure sensitivity and load sensitivity of different tires but provides no possibility of measuring accurately whether one tire will fundamentally have a higher or lower rolling resistance than another." (emphasis added)

There are several apparent significant conflicts expressed in the above statements which typify the comments received in this area. The commentors prefer the simpler tests and demand proof that the more complex tests are representative of in-use results before they wish to experiment with these procedures. However, for the simpler SAE proposed procedure no "proof" of representativeness is demanded, even though the above quotation demonstrates that some members of the SAE Rolling Resistance Committee recognize fundamental inadequacies in the current SAE approach. In the presence of the known current problems of the SAE draft procedure, it is illogical for EPA to adopt this approach.

One commentor suggested that the proposed SAE procedure be adopted with the additional monitoring of the tire energy dissipation during the warm-up period. If the SAE procedure were modified to include the warm-up phase of the tire under "capped air" conditions, this suggested approach would be similar to the proposed EPA procedure. However, even with this approach, some data manipulation would be required to evaluate the tire energy dissipation during periods of the tire warm-up. The proposed EPA procedure accomplishes this relative weighting by requiring operation of the tire over two distinct low and high speed segments. The average values of the tire energy dissipation may then be conveniently analyzed for each test segment. It is concluded that the proposed EPA procedure is preferred over either the current SAE procedure, or a modified SAE procedure, which would obtain data during tire warm-up. It is noted that the EPA approach could easily be adopted as the warm-up phase of the current SAE procedure. This would incure a slight additional test time for each tire compared with the current SAE procedure, but would provide both the desired thermally transient and pressure/load sensitivity test results. This incorporation of the EPA proposed procedure as the warm-up phase for the SAE procedure is recommended.

In a different area, one commentor recommended that the minimum roll diameter should be 1.5m instead of the current 1m. It is the opinion of this reviewer that tire testing techniques should be tending toward flat bed test machines. The use of a cylindrical test surface was provided to allow use of most of the current tire dynamometers. The choice of the minimum diameter was also chosen for this reason. Since there is no reason to encourage the use of 1m test machines, a minimum test machine diameter of at least 1.5m should be specified if this does not prohibit the use of current test machines.

V. Conclusions and Recommendations

A. It is concluded that:

1. The proposed force transient procedure is physically feasible, it may have some variability problems which are not yet resolved, and it could not be conducted using existing test equipment. It is therefore concluded that this procedure is not practical at the present time.

2. The proposed temperature transient procedure is feasible, and can be conducted on many existing test machines. However, additional data acquisition equipment may be necessary in some cases.

3. The proposed EPA temperature transient procedure for determining tire energy dissipation is superior to the proposed SAE procedure for comparing tires in a manner which is more likely to reflect the consumer experience of the tire.

4. The minimum roll diameter should be increased to at least 1.5m.

B. It is recommended that:

1. Efforts be continued to demonstrate the practicality and possible necessity of the force transient procedure. This work is currently in progress by contract with the Pennsylvania Transportation Institute.

2. The proposed EPA temperature transient cycle should remain as the recommended EPA practice at the present time. Efforts should be made to compare the results of this procedure to that of the draft SAE procedure if SAE retains their current procedure. One tire and one automobile manufacturer have offered to assist in this comparison, and these offers of assistance should be accepted.

3. The minimum diameter of the acceptable test surface should be increased to at least 1.5m, and preferably it should be 1.7m (67 inches).

Attachment I

EPA TECHNICAL REPORT

"Determination of Tire Energy
Dissipation Analysis and Recommended
Practices"

Technical Report

Determination of Tire Energy Dissipation Analysis and Recommended Practices

April 1978

by

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Notice

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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

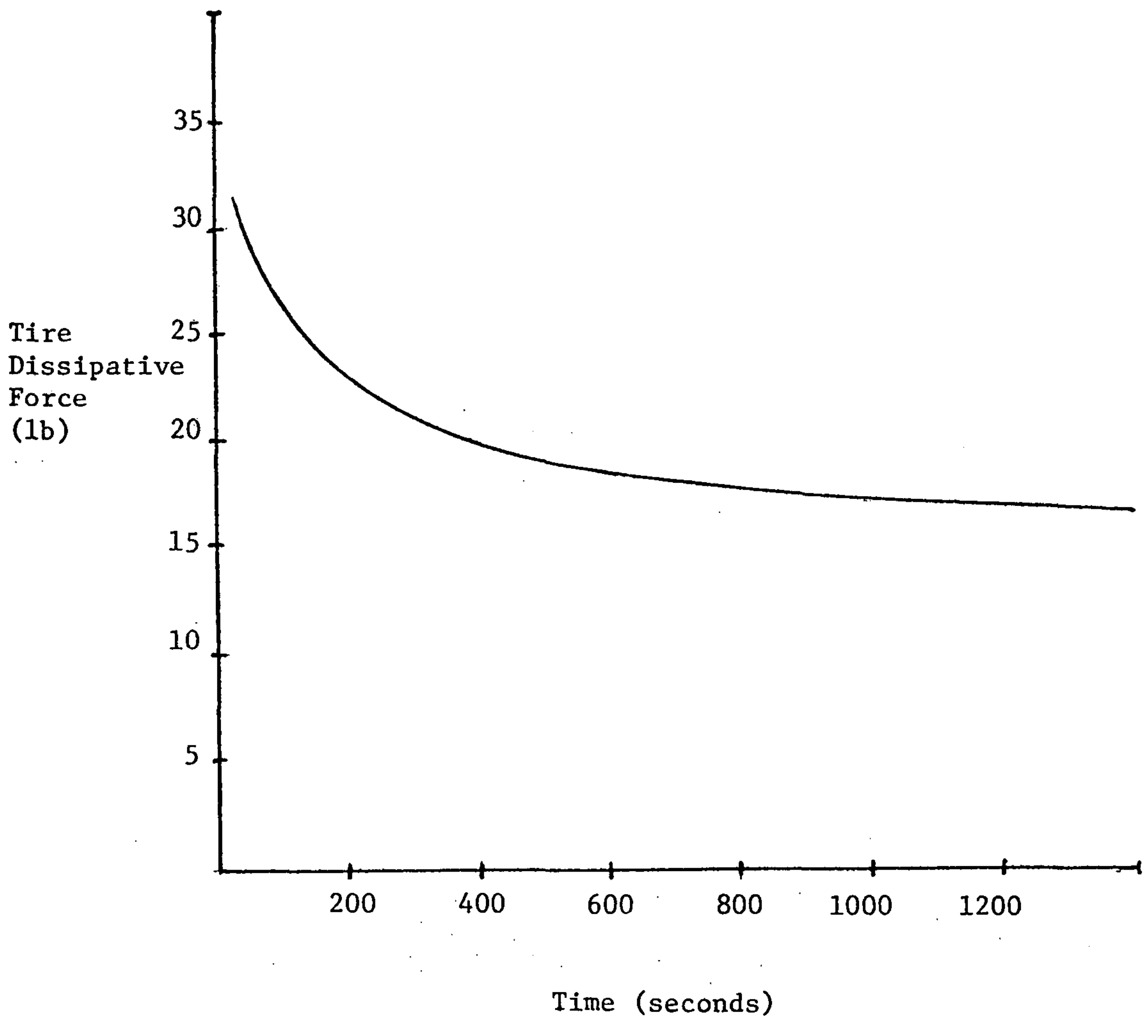


Figure 1 - Typical Tire Energy Dissipation
Force vs. Time

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

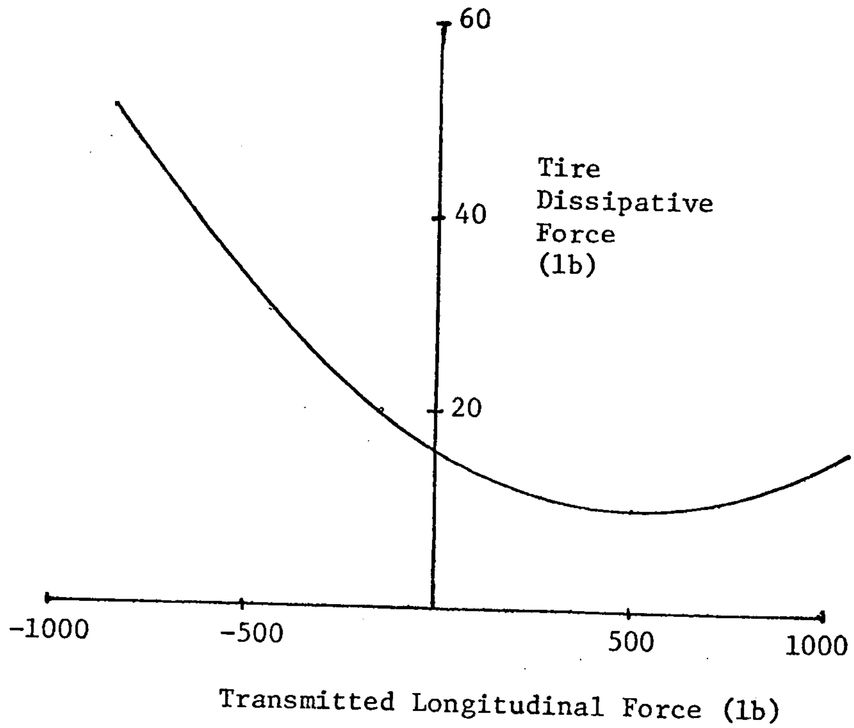


Figure 2 - Tire Energy Dissipative
Force is Transmitted Force

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 $\pm$ 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 $\pm$ 1 mm ($\pm$ 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 $\pm$ 2°C (68°F $\pm$ 4°F).

2. Tire Inflation Pressure Gauges - The gauges used to measure the tire inflation pressures shall be accurate to within $\pm$ 0.5 kPaG ($\pm$ 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 $\pm$ 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 $\pm 1°$

- Slip angle $0 \pm 0.25°$

- Camber angle $0° \pm 0.50°$

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 $\pm$ 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

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

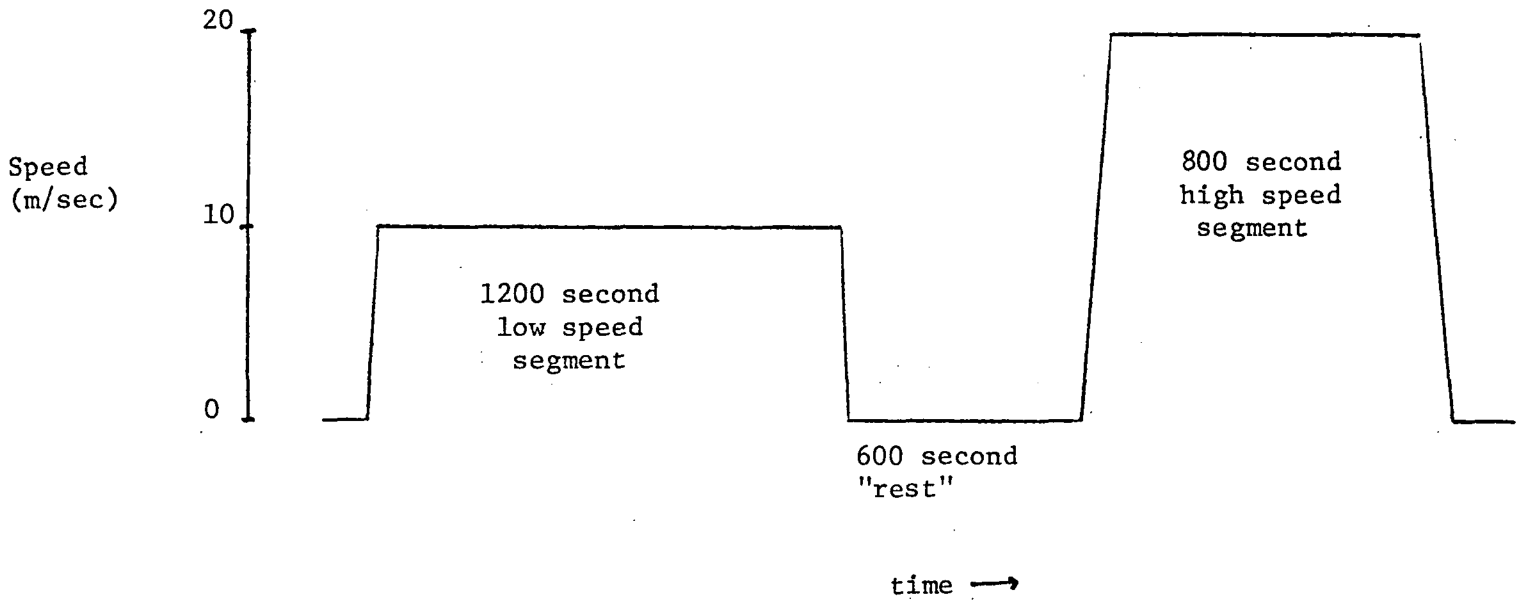
It should be noted that e is a dimensionless coefficient and is equivalent to the average rolling resistance coefficient over the test cycle.

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 $\pm$ 1 nt.

3. Test Speed - The machine shall be capable of maintaining the desired test schedule speed to within $\pm$ 1 m/sec (2 mi/hr) and shall be capable of measuring this speed to within $\pm$ 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 $\pm$ 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 $\pm$ 1 mm ($\pm$ 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° $\pm$ 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 $\pm$ 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

1	0.0	61	24.60	121	12.10	181	27.20	241	56.70
2	0.0	62	24.90	122	8.40	182	26.50	242	56.50
3	0.0	63	25.00	123	5.50	183	24.00	243	56.50
4	0.0	64	24.60	124	2.20	184	22.70	244	56.50
5	0.0	65	24.50	125	0.0	185	19.40	245	56.50
6	0.0	66	24.70	126	0.0	186	17.70	246	56.50
7	0.0	67	24.80	127	0.0	187	17.20	247	56.50
8	0.0	68	24.70	128	0.0	188	18.10	248	56.40
9	0.0	69	24.60	129	0.0	189	18.60	249	56.10
10	0.0	70	24.60	130	0.0	190	20.00	250	55.80
11	0.0	71	25.10	131	0.0	191	22.20	251	55.10
12	0.0	72	25.60	132	0.0	192	24.50	252	54.60
13	0.0	73	25.70	133	0.0	193	27.30	253	54.20
14	0.0	74	25.40	134	0.0	194	30.50	254	54.00
15	0.0	75	24.90	135	0.0	195	33.50	255	53.70
16	0.0	76	25.00	136	0.0	196	36.20	256	53.60
17	0.0	77	25.40	137	0.0	197	37.30	257	53.90
18	0.0	78	26.00	138	0.0	198	39.30	258	54.00
19	0.0	79	26.00	139	0.0	199	40.50	259	54.10
20	0.0	80	25.70	140	0.0	200	42.10	260	54.10
21	3.00	81	26.10	141	0.0	201	43.50	261	53.80
22	5.90	82	26.70	142	0.0	202	45.10	262	53.40
23	8.60	83	27.50	143	0.0	203	46.00	263	53.00
24	11.50	84	28.60	144	0.0	204	46.80	264	52.60
25	14.30	85	29.30	145	0.0	205	47.50	265	52.10
26	16.90	86	29.80	146	0.0	206	47.50	266	52.40
27	17.30	87	30.10	147	0.0	207	47.30	267	52.00
28	18.10	88	30.40	148	0.0	208	47.20	268	51.90
29	20.70	89	30.70	149	0.0	209	47.00	269	51.70
30	21.70	90	30.70	150	0.0	210	47.00	270	51.50
31	22.40	91	30.50	151	0.0	211	47.00	271	51.60
32	22.50	92	30.40	152	0.0	212	47.00	272	51.80
33	22.10	93	30.30	153	0.0	213	47.00	273	52.10
34	21.50	94	30.40	154	0.0	214	47.20	274	52.50
35	20.90	95	30.80	155	0.0	215	47.40	275	53.00
36	20.40	96	30.40	156	0.0	216	47.90	276	53.50
37	19.80	97	29.90	157	0.0	217	48.50	277	54.00
38	17.00	98	29.50	158	0.0	218	49.10	278	54.90
39	14.90	99	29.80	159	0.0	219	49.50	279	55.40
40	14.90	100	30.30	160	0.0	220	50.00	280	55.60
41	15.20	101	30.70	161	0.0	221	50.60	281	56.00
42	15.50	102	30.90	162	0.0	222	51.00	282	56.00
43	16.00	103	31.00	163	0.0	223	51.50	283	55.80
44	17.10	104	30.90	164	3.30	224	52.20	284	55.20
45	19.10	105	30.40	165	6.60	225	53.20	285	54.50
46	21.10	106	29.80	166	9.90	226	54.10	286	53.60
47	22.70	107	29.90	167	13.20	227	54.60	287	52.50
48	22.90	108	30.20	168	16.50	228	54.90	288	51.50
49	22.70	109	30.70	169	19.80	229	55.00	289	51.50
50	22.60	110	31.20	170	22.20	230	54.90	290	51.50
51	21.30	111	31.80	171	24.30	231	54.60	291	51.10
52	19.00	112	32.20	172	25.80	232	54.60	292	50.10
53	17.10	113	32.40	173	26.40	233	54.80	293	50.00
54	15.80	114	32.20	174	25.70	234	55.10	294	50.10
55	15.80	115	31.70	175	25.10	235	55.50	295	50.00
56	17.70	116	28.60	176	24.70	236	55.70	296	49.60
57	19.80	117	25.30	177	25.00	237	56.10	297	49.50
58	21.60	118	22.00	178	25.20	238	56.30	298	49.50
59	23.20	119	18.70	179	25.40	239	56.60	299	49.50
60	24.20	120	15.40	180	25.80	240	56.70	300	49.10

301	48.60	361	31.60	421	25.00	481	35.00	541	25.00
302	48.10	362	32.10	422	21.70	482	35.10	542	25.00
303	47.20	363	32.80	423	18.40	483	35.20	543	25.00
304	46.10	364	33.60	424	15.10	484	35.50	544	24.40
305	45.00	365	34.50	425	11.80	485	35.20	545	23.10
306	43.80	366	34.60	426	8.50	486	35.00	546	19.80
307	42.60	367	34.90	427	5.20	487	35.00	547	16.50
308	41.50	368	34.80	428	1.90	488	35.00	548	13.20
309	40.30	369	34.50	429	0.0	489	34.80	549	9.90
310	38.50	370	34.70	430	0.0	490	34.60	550	6.60
311	37.00	371	35.50	431	0.0	491	34.50	551	3.30
312	35.20	372	36.00	432	0.0	492	33.50	552	0.0
313	33.80	373	36.00	433	0.0	493	32.00	553	0.0
314	32.50	374	36.00	434	0.0	494	30.10	554	0.0
315	31.50	375	36.00	435	0.0	495	28.00	555	0.0
316	30.60	376	36.00	436	0.0	496	25.50	556	0.0
317	30.50	377	36.00	437	0.0	497	22.50	557	0.0
318	30.00	378	36.10	438	0.0	498	19.80	558	0.0
319	29.00	379	36.40	439	0.0	499	16.50	559	0.0
320	27.50	380	36.50	440	0.0	500	13.20	560	0.0
321	24.80	381	36.40	441	0.0	501	10.30	561	0.0
322	21.50	382	36.00	442	0.0	502	7.20	562	0.0
323	20.10	383	35.10	443	0.0	503	4.00	563	0.0
324	19.10	384	34.10	444	0.0	504	1.00	564	0.0
325	18.50	385	33.50	445	0.0	505	0.0	565	0.0
326	17.00	386	31.40	446	0.0	506	0.0	566	0.0
327	15.50	387	29.00	447	0.0	507	0.0	567	0.0
328	12.50	388	25.70	448	3.30	508	0.0	568	0.0
329	10.80	389	23.00	449	6.60	509	0.0	569	3.30
330	8.00	390	20.30	450	9.90	510	0.0	570	6.60
331	4.70	391	17.50	451	13.20	511	1.20	571	9.90
332	1.40	392	14.50	452	16.50	512	3.50	572	13.00
333	0.0	393	12.00	453	19.80	513	5.50	573	14.60
334	0.0	394	8.70	454	23.10	514	6.50	574	16.00
335	0.0	395	5.40	455	26.40	515	8.50	575	17.00
336	0.0	396	2.10	456	27.80	516	9.60	576	17.00
337	0.0	397	0.0	457	29.10	517	10.50	577	17.00
338	0.0	398	0.0	458	31.50	518	11.90	578	17.50
339	0.0	399	0.0	459	33.00	519	14.00	579	17.70
340	0.0	400	0.0	460	33.60	520	16.00	580	17.70
341	0.0	401	0.0	461	34.80	521	17.70	581	17.50
342	0.0	402	0.0	462	35.10	522	19.00	582	17.00
343	0.0	403	2.60	463	35.60	523	20.10	583	16.90
344	0.0	404	5.90	464	36.10	524	21.00	584	16.60
345	0.0	405	9.20	465	36.00	525	22.00	585	17.00
346	0.0	406	12.50	466	36.10	526	23.00	586	17.10
347	1.00	407	15.80	467	36.20	527	23.80	587	17.00
348	4.30	408	19.10	468	36.00	528	24.50	588	16.60
349	7.60	409	22.40	469	35.70	529	24.90	589	16.50
350	10.90	410	25.00	470	36.00	530	25.00	590	16.50
351	14.20	411	25.60	471	36.00	531	25.00	591	16.60
352	17.30	412	27.50	472	35.60	532	25.00	592	17.00
353	20.00	413	29.00	473	35.50	533	25.00	593	17.60
354	22.50	414	30.00	474	35.40	534	25.00	594	18.50
355	23.70	415	30.10	475	35.20	535	25.00	595	19.20
356	25.20	416	30.00	476	35.20	536	25.60	596	20.20
357	26.60	417	29.70	477	35.20	537	25.80	597	21.00
358	28.10	418	29.30	478	35.20	538	26.00	598	21.10
359	30.00	419	28.80	479	35.20	539	25.60	599	21.20
360	30.80	420	28.00	480	35.20	540	25.20	600	21.60

601	22.00	661	26.00	721	12.00	781	28.00	841	19.20
602	22.40	662	26.10	722	4.00	782	28.30	842	20.10
603	22.50	663	26.20	723	6.20	783	28.90	843	20.90
604	22.50	664	26.20	724	4.50	784	28.90	844	21.40
605	22.50	665	26.40	725	3.00	785	28.90	845	22.00
606	22.70	666	26.50	726	2.10	786	28.80	846	22.60
607	23.70	667	26.50	727	0.50	787	28.50	847	23.20
608	25.10	668	26.00	728	0.50	788	28.30	848	24.00
609	26.00	669	25.50	729	3.20	789	28.30	849	25.00
610	26.50	670	23.60	730	6.50	790	28.30	850	26.00
611	27.00	671	21.40	731	9.60	791	28.20	851	26.60
612	26.10	672	18.50	732	12.50	792	27.60	852	26.60
613	22.80	673	16.40	733	14.00	793	27.50	853	26.80
614	19.50	674	14.50	734	16.00	794	27.50	854	27.00
615	16.20	675	11.60	735	18.00	795	27.50	855	27.20
616	12.90	676	8.70	736	19.60	796	27.50	856	27.80
617	9.60	677	5.80	737	21.50	797	27.50	857	28.10
618	6.30	678	3.50	738	23.10	798	27.50	858	28.80
619	3.00	679	2.00	739	24.50	799	27.60	859	28.90
620	0.0	680	0.0	740	25.50	800	28.00	860	29.00
621	0.0	681	0.0	741	26.50	801	26.50	861	29.10
622	0.0	682	0.0	742	27.10	802	30.00	862	29.00
623	0.0	683	0.0	743	27.60	803	31.00	863	28.10
624	0.0	684	0.0	744	27.90	804	32.00	864	27.50
625	0.0	685	0.0	745	28.30	805	33.00	865	27.00
626	0.0	686	0.0	746	28.60	806	33.00	866	25.80
627	0.0	687	0.0	747	28.60	807	33.60	867	25.00
628	0.0	688	0.0	748	28.30	808	34.00	868	24.50
629	0.0	689	0.0	749	28.20	809	34.30	869	24.80
630	0.0	690	0.0	750	28.00	810	34.20	870	25.10
631	0.0	691	0.0	751	27.50	811	34.00	871	25.50
632	0.0	692	0.0	752	26.60	812	34.00	872	25.70
633	0.0	693	0.0	753	25.50	813	33.90	873	26.20
634	0.0	694	1.40	754	23.50	814	33.60	874	26.90
635	0.0	695	3.30	755	21.50	815	33.10	875	27.50
636	0.0	696	4.40	756	19.00	816	33.00	876	27.80
637	0.0	697	6.50	757	16.50	817	32.50	877	28.40
638	0.0	698	9.20	758	14.90	818	32.00	878	29.00
639	0.0	699	11.30	759	12.50	819	31.90	879	29.20
640	0.0	700	13.50	760	9.40	820	31.60	880	29.10
641	0.0	701	14.60	761	6.20	821	31.50	881	29.00
642	0.0	702	16.40	762	3.00	822	30.60	882	28.90
643	0.0	703	16.70	763	1.50	823	30.00	883	28.50
644	0.0	704	16.50	764	1.50	824	29.90	884	28.10
645	0.0	705	16.50	765	0.50	825	29.90	885	28.00
646	2.00	706	18.20	766	0.0	826	29.90	886	28.00
647	4.50	707	19.20	767	3.00	827	29.90	887	27.60
648	7.80	708	20.10	768	6.30	828	29.60	888	27.20
649	10.20	709	21.50	769	9.60	829	29.50	889	26.60
650	12.50	710	22.50	770	12.90	830	29.50	890	27.00
651	14.00	711	22.50	771	15.80	831	29.30	891	27.50
652	15.30	712	22.10	772	17.50	832	25.90	892	27.80
653	17.50	713	22.70	773	18.40	833	28.20	893	28.00
654	19.60	714	23.30	774	19.50	834	27.70	894	27.80
655	21.00	715	23.50	775	20.70	835	27.00	895	28.00
656	22.20	716	22.50	776	22.00	836	25.50	896	28.00
657	23.30	717	21.60	777	23.20	837	23.70	897	28.00
658	24.50	718	20.50	778	25.00	838	22.00	898	27.70
659	25.30	719	18.00	779	26.50	839	20.50	899	27.40
660	25.60	720	15.00	780	27.50	840	19.20	900	26.90

901	26.60	961	5.30	1021	4.30	1081	15.00	1141	25.50
902	26.50	962	8.60	1022	1.00	1082	12.30	1142	24.60
903	26.50	963	11.90	1023	0.0	1083	11.10	1143	23.50
904	26.50	964	15.20	1024	0.0	1084	10.60	1144	21.50
905	26.30	965	17.50	1025	0.0	1085	10.00	1145	20.00
906	26.20	966	18.60	1026	0.0	1086	9.50	1146	17.50
907	26.20	967	20.00	1027	0.0	1087	9.10	1147	16.00
908	25.90	968	21.10	1028	0.0	1088	8.70	1148	14.00
909	25.60	969	22.00	1029	0.0	1089	8.60	1149	10.70
910	25.60	970	23.00	1030	0.0	1090	8.80	1150	7.40
911	25.90	971	24.50	1031	0.0	1091	9.00	1151	4.10
912	25.80	972	26.30	1032	0.0	1092	8.70	1152	0.80
913	25.50	973	27.50	1033	0.0	1093	8.60	1153	0.0
914	24.60	974	28.10	1034	0.0	1094	8.00	1154	0.0
915	23.50	975	28.40	1035	0.0	1095	7.00	1155	0.0
916	22.20	976	28.50	1036	0.0	1096	5.00	1156	0.0
917	21.60	977	28.50	1037	0.0	1097	4.20	1157	0.0
918	21.60	978	28.50	1038	0.0	1098	2.60	1158	0.0
919	21.70	979	27.70	1039	0.0	1099	1.00	1159	0.0
920	22.60	980	27.50	1040	0.0	1100	0.0	1160	0.0
921	23.40	981	27.20	1041	0.0	1101	0.10	1161	0.0
922	24.00	982	26.80	1042	0.0	1102	0.60	1162	0.0
923	24.20	983	26.50	1043	0.0	1103	1.60	1163	0.0
924	24.40	984	26.00	1044	0.0	1104	3.60	1164	0.0
925	24.90	985	25.70	1045	0.0	1105	6.90	1165	0.0
926	25.10	986	25.20	1046	0.0	1106	10.00	1166	0.0
927	25.20	987	24.00	1047	0.0	1107	12.80	1167	0.0
928	25.30	988	22.00	1048	0.0	1108	14.00	1168	0.0
929	25.50	989	21.50	1049	0.0	1109	14.50	1169	2.10
930	25.20	990	21.50	1050	0.0	1110	16.00	1170	5.40
931	25.00	991	21.80	1051	0.0	1111	18.10	1171	8.70
932	25.00	992	22.50	1052	0.0	1112	20.00	1172	12.00
933	25.00	993	23.00	1053	1.20	1113	21.00	1173	15.30
934	24.70	994	22.80	1054	4.00	1114	21.20	1174	18.60
935	24.50	995	22.80	1055	7.30	1115	21.30	1175	21.10
936	24.30	996	23.00	1056	10.60	1116	21.40	1176	23.00
937	24.30	997	22.70	1057	13.90	1117	21.70	1177	23.50
938	24.50	998	22.70	1058	17.00	1118	22.50	1178	23.00
939	25.00	999	22.70	1059	18.50	1119	23.00	1179	22.50
940	25.00	1000	23.50	1060	20.00	1120	23.80	1180	20.00
941	24.60	1001	24.00	1061	21.80	1121	24.50	1181	16.70
942	24.60	1002	24.60	1062	23.00	1122	25.00	1182	13.40
943	24.10	1003	24.80	1063	24.00	1123	24.90	1183	10.10
944	24.50	1004	25.10	1064	24.80	1124	24.80	1184	6.80
945	25.10	1005	25.50	1065	25.60	1125	25.00	1185	3.50
946	25.60	1006	25.60	1066	26.50	1126	25.40	1186	0.20
947	25.10	1007	25.50	1067	26.80	1127	25.80	1187	0.0
948	24.00	1008	25.00	1068	27.40	1128	26.00	1188	0.0
949	22.00	1009	24.10	1069	27.90	1129	26.40	1189	0.0
950	20.10	1010	23.70	1070	28.30	1130	26.60	1190	0.0
951	16.90	1011	23.20	1071	28.00	1131	26.90	1191	0.0
952	13.60	1012	22.90	1072	27.50	1132	27.00	1192	0.0
953	10.30	1013	22.50	1073	27.00	1133	27.00	1193	0.0
954	7.00	1014	22.00	1074	27.00	1134	27.00	1194	0.0
955	3.70	1015	21.60	1075	26.30	1135	26.90	1195	0.0
956	0.40	1016	20.50	1076	24.50	1136	26.80	1196	0.0
957	0.0	1017	17.50	1077	22.50	1137	26.80	1197	0.20
958	0.0	1018	14.20	1078	21.50	1138	26.50	1198	1.50
959	0.0	1019	10.90	1079	20.60	1139	26.40	1199	3.50
960	2.00	1020	7.60	1080	18.00	1140	26.00	1200	6.50

1201	9.80	1261	4.70	1321	0.0
1202	12.00	1262	4.00	1322	0.0
1203	12.90	1263	19.00	1323	0.0
1204	13.00	1264	16.50	1324	0.0
1205	12.60	1265	9.50	1325	0.0
1206	12.80	1266	4.50	1326	0.0
1207	13.10	1267	7.60	1327	0.0
1208	13.10	1268	8.50	1328	0.0
1209	14.00	1269	11.00	1329	0.0
1210	15.50	1270	14.00	1330	0.0
1211	17.00	1271	17.00	1331	0.0
1212	18.60	1272	19.50	1332	0.0
1213	19.70	1273	21.00	1333	0.0
1214	21.00	1274	21.80	1334	0.0
1215	21.50	1275	22.20	1335	0.0
1216	21.80	1276	23.00	1336	0.0
1217	21.80	1277	23.60	1337	0.0
1218	21.50	1278	24.10	1338	1.50
1219	21.20	1279	24.50	1339	4.80
1220	21.50	1280	24.50	1340	8.10
1221	21.80	1281	24.00	1341	11.40
1222	22.00	1282	23.50	1342	13.20
1223	21.90	1283	23.50	1343	15.10
1224	21.70	1284	23.50	1344	16.80
1225	21.50	1285	23.50	1345	18.30
1226	21.50	1286	23.50	1346	19.50
1227	21.40	1287	23.50	1347	20.30
1228	20.10	1288	24.00	1348	21.30
1229	19.50	1289	24.10	1349	21.90
1230	19.20	1290	24.50	1350	22.10
1231	19.60	1291	24.70	1351	22.40
1232	19.80	1292	25.00	1352	22.00
1233	20.00	1293	25.40	1353	21.60
1234	19.50	1294	25.60	1354	21.10
1235	17.50	1295	25.70	1355	20.50
1236	15.50	1296	26.00	1356	20.00
1237	13.00	1297	26.20	1357	19.60
1238	10.00	1298	27.00	1358	18.50
1239	8.00	1299	27.80	1359	17.50
1240	6.00	1300	28.30	1360	16.50
1241	4.00	1301	29.00	1361	15.50
1242	2.50	1302	29.10	1362	14.00
1243	0.70	1303	29.00	1363	11.00
1244	0.0	1304	28.00	1364	8.00
1245	0.0	1305	24.70	1365	5.20
1246	0.0	1306	21.40	1366	2.50
1247	0.0	1307	18.10	1367	0.0
1248	0.0	1308	14.80	1368	0.0
1249	0.0	1309	11.50	1369	0.0
1250	0.0	1310	8.20	1370	0.0
1251	0.0	1311	4.90	1371	0.0
1252	1.00	1312	1.60	1372	0.0
1253	1.00	1313	0.0		
1254	1.00	1314	0.0		
1255	1.00	1315	0.0		
1256	1.00	1316	0.0		
1257	1.60	1317	0.0		
1258	3.00	1318	0.0		
1259	4.00	1319	0.0		
1260	5.00	1320	0.0		

1	0.0	61	44.8	121	47.7	181	42.2	241	46.9
2	0.0	62	44.93	122	47.37	182	41.54	242	46.64
3	2.0	63	45.03	123	47.30	183	41.50	243	46.86
4	4.90	64	45.1	124	47.5	184	42.1	244	47.0
5	8.10	65	45.36	125	47.76	185	42.90	245	47.20
6	11.30	66	45.66	126	47.93	186	43.50	246	47.50
7	14.5	67	46.0	127	48.0	187	43.9	247	47.9
8	17.30	68	46.26	128	47.94	188	43.64	248	47.96
9	19.60	69	46.53	129	47.90	189	43.33	249	48.00
10	21.6	70	46.8	130	47.9	190	43.0	250	48.0
11	24.00	71	46.93	131	47.96	191	43.06	251	48.00
12	25.76	72	47.03	132	48.00	192	43.36	252	48.03
13	27.1	73	47.1	133	48.0	193	43.9	253	48.1
14	28.03	74	47.23	134	47.94	194	44.30	254	48.16
15	29.60	75	47.27	135	47.27	195	44.63	255	48.17
16	30.0	76	47.2	136	46.0	196	44.9	256	48.1
17	30.73	77	47.07	137	43.34	197	44.77	257	48.56
18	31.46	78	46.97	138	41.17	198	44.43	258	48.90
19	32.2	79	46.9	139	39.5	199	43.9	259	49.1
20	32.85	80	46.90	140	39.17	200	43.44	260	49.10
21	33.50	81	46.93	141	39.00	201	43.20	261	49.10
22	34.1	82	47.0	142	39.0	202	43.2	262	49.1
23	34.56	83	47.06	143	39.13	203	43.07	263	49.10
24	34.90	84	47.13	144	39.50	204	43.00	264	49.03
25	35.1	85	47.2	145	40.1	205	43.0	265	48.9
26	35.70	86	47.14	146	41.03	206	43.06	266	48.17
27	35.43	87	47.03	147	42.03	207	43.36	267	47.70
28	35.5	88	46.9	148	43.1	208	43.4	268	47.5
29	35.34	89	46.50	149	43.70	209	43.46	269	47.17
30	34.90	90	46.27	150	44.10	210	43.53	270	46.73
31	34.5	91	46.2	151	44.3	211	42.5	271	46.2
32	34.53	92	46.26	152	44.43	212	41.54	272	46.00
33	34.83	93	46.50	153	44.56	213	40.67	273	45.50
34	35.1	94	46.9	154	44.7	214	40.0	274	45.5
35	35.70	95	47.10	155	44.90	215	40.00	275	45.40
36	36.16	96	47.36	156	45.23	216	40.33	276	45.20
37	36.2	97	47.7	157	45.7	217	41.0	277	45.0
38	36.46	98	47.96	158	45.90	218	42.00	278	44.74
39	36.70	99	48.23	159	46.26	219	42.70	279	44.47
40	36.9	100	48.5	160	46.8	220	43.1	280	44.2
41	36.56	101	48.83	161	46.86	221	43.16	281	43.54
42	37.00	102	49.06	162	46.96	222	43.43	282	42.90
43	37.0	103	49.2	163	47.1	223	43.9	283	42.0
44	37.00	104	49.14	164	47.56	224	44.30	284	41.14
45	37.00	105	49.07	165	47.86	225	44.70	285	38.63
46	37.0	106	49.0	166	48.0	226	45.1	286	37.5
47	37.06	107	49.00	167	48.00	227	45.36	287	35.44
48	37.33	108	49.06	168	47.93	228	45.83	288	34.57
49	37.8	109	49.2	169	47.8	229	46.9	289	34.0
50	38.60	110	49.33	170	47.27	230	46.90	290	33.27
51	39.33	111	49.43	171	46.73	231	47.20	291	32.50
52	40.0	112	49.5	172	46.2	232	47.4	292	31.7
53	40.66	113	49.50	173	45.94	233	47.34	293	30.57
54	41.40	114	49.47	174	45.70	234	47.27	294	29.50
55	42.2	115	49.4	175	45.5	235	47.2	295	28.8
56	42.93	116	49.14	176	45.44	236	47.20	296	28.40
57	43.53	117	48.87	177	45.27	237	47.17	297	28.63
58	44.0	118	48.8	178	45.0	238	47.1	298	29.9
59	44.26	119	48.40	179	44.00	239	47.04	299	31.36
60	44.53	120	48.10	180	43.07	240	46.97	300	33.40

301	35.6	361	57.2	421	59.8	481	55.0	541	[illegible]
302	37.53	362	57.07	422	59.86	482	54.94	542	[illegible]
303	39.06	363	57.00	423	59.87	483	54.90	543	[illegible]
304	40.2	364	57.0	424	59.8	484	54.9	544	[illegible]
305	41.06	365	56.94	425	59.60	485	54.90	545	[illegible]
306	41.80	366	56.90	426	59.40	486	54.90	546	[illegible]
307	42.4	367	56.9	427	59.2	487	54.9	547	[illegible]
308	42.80	368	56.96	428	59.07	488	54.96	548	[illegible]
309	43.26	369	57.00	429	58.97	489	55.00	549	55.87
310	43.8	370	57.0	430	58.9	490	55.0	550	55.8
311	44.33	371	57.00	431	58.70	491	55.00	551	55.60
312	44.73	372	57.00	432	58.57	492	55.00	552	55.40
313	45.0	373	57.0	433	58.5	493	55.0	553	55.2
314	45.20	374	57.00	434	58.44	494	55.06	554	55.07
315	45.36	375	57.00	435	58.37	495	55.07	555	54.97
316	45.5	376	57.0	436	58.3	496	55.0	556	54.9
317	45.76	377	56.94	437	58.17	497	54.94	557	[illegible]
318	45.96	378	56.77	438	58.07	498	54.87	558	54.40
319	46.1	379	56.5	439	58.0	499	54.8	559	54.2
320	46.50	380	56.17	440	57.94	500	54.74	560	[illegible]
321	46.83	381	56.00	441	57.90	501	54.60	561	[illegible]
322	47.1	382	56.0	442	57.9	502	54.4	562	53.4
323	47.70	383	56.00	443	57.90	503	54.34	563	[illegible]
324	[illegible]	384	55.13	444	57.93	504	54.27	564	[illegible]
325	[illegible]	385	55.4	445	58.0	505	54.2	565	[illegible]
326	[illegible]	386	[illegible]	446	58.06	506	54.14	566	[illegible]
327	50.33	387	56.40	447	58.13	507	54.10	567	[illegible]
328	51.0	388	57.1	448	58.2	508	54.1	568	[illegible]
329	51.73	389	57.30	449	58.20	509	[illegible]	569	[illegible]
330	[illegible]	390	57.40	450	58.17	510	[illegible]	570	[illegible]
331	53.1	391	57.4	451	[illegible]	511	[illegible]	571	[illegible]
332	[illegible]	392	57.20	452	[illegible]	512	[illegible]	572	[illegible]
333	[illegible]	393	[illegible]	453	[illegible]	513	[illegible]	573	[illegible]
334	[illegible]	394	56.9	454	[illegible]	514	[illegible]	574	[illegible]
335	[illegible]	395	56.57	455	[illegible]	515	[illegible]	575	[illegible]
336	[illegible]	396	[illegible]	456	[illegible]	516	[illegible]	576	[illegible]
337	[illegible]	397	[illegible]	457	[illegible]	517	[illegible]	577	[illegible]
338	[illegible]	398	[illegible]	458	[illegible]	518	[illegible]	578	[illegible]
339	57.10	399	56.70	459	[illegible]	519	[illegible]	579	[illegible]
340	57.3	400	57.1	460	[illegible]	520	[illegible]	580	[illegible]
341	57.56	401	57.50	461	58.06	521	[illegible]	581	[illegible]
342	57.80	402	57.80	462	58.13	522	[illegible]	582	[illegible]
343	58.0	403	58.0	463	58.2	523	[illegible]	583	[illegible]
344	58.13	404	58.00	464	58.26	524	55.16	584	[illegible]
345	58.36	405	58.00	465	58.30	525	[illegible]	585	[illegible]
346	58.7	406	58.0	466	58.3	526	55.3	586	[illegible]
347	58.83	407	58.00	467	58.17	527	55.43	587	[illegible]
348	58.93	408	57.97	468	58.07	528	55.53	588	[illegible]
349	59.0	409	57.9	469	58.0	529	55.6	589	[illegible]
350	59.00	410	57.77	470	57.80	530	55.73	590	[illegible]
351	58.93	411	57.70	471	57.50	531	55.83	591	[illegible]
352	58.8	412	57.7	472	57.1	532	55.9	592	[illegible]
353	58.60	413	57.76	473	56.97	533	55.96	593	[illegible]
354	58.40	414	57.86	474	56.63	534	56.00	594	49.10
355	58.2	415	58.0	475	56.1	535	56.0	595	49.1
356	58.07	416	58.13	476	56.04	536	56.00	596	[illegible]
357	57.97	417	58.43	477	55.83	537	56.00	597	[illegible]
358	57.9	418	58.9	478	55.5	538	56.0	598	48.9
359	57.64	419	59.10	479	55.24	539	56.00	599	48.57
360	57.40	420	59.40	480	55.07	540	56.00	600	48.27

601	48.0	661	51.1	721	58.5
602	47.87	662	51.36	722	58.10
603	47.77	663	51.66	723	57.70
604	47.7	664	52.0	724	57.3
605	47.90	665	52.20	725	57.10
606	48.33	666	52.46	726	56.83
607	49.0	667	52.8	727	56.5
608	49.06	668	52.74	728	56.17
609	49.03	669	52.57	729	55.53
610	48.9	670	52.3	730	54.6
611	47.97	671	52.30	731	54.14
612	47.07	672	52.36	732	53.67
613	46.2	673	52.5	733	53.2
614	46.07	674	52.70	734	52.87
615	46.06	675	52.67	735	52.47
616	46.2	676	52.4	736	52.0
617	46.86	677	52.14	737	51.34
618	47.80	678	51.70	738	50.50
619	49.0	679	51.1	739	49.5
620	49.73	680	50.50	740	48.50
621	50.56	681	50.07	741	47.60
622	51.5	682	49.8	742	46.8
623	52.16	683	49.67	743	45.60
624	52.66	684	49.57	744	44.17
625	53.0	685	49.5	745	42.5
626	53.60	686	49.50	746	39.20
627	53.96	687	49.66	747	35.90
628	54.1	688	50.0	748	32.6
629	54.36	689	50.20	749	29.30
630	54.70	690	50.56	750	26.80
631	55.1	691	51.1	751	24.50
632	55.43	692	51.56	752	21.5
633	55.40	693	51.66	753	19.50
634	55.0	694	52.0	754	17.37
635	54.47	695	52.06	755	15.1
636	53.63	696	52.36	756	12.44
637	52.5	697	52.9	757	9.73
638	50.17	698	53.30	758	7.0
639	48.17	699	53.73	759	5.00
640	46.5	700	54.2	760	3.33
641	46.17	701	54.53	761	2.0
642	46.00	702	54.80	762	0.67
643	46.0	703	55.0	763	0.00
644	46.33	704	55.53	764	0.00
645	46.83	705	55.90	765	0.00
646	47.5	706	56.1		
647	48.16	707	56.30		
648	48.83	708	56.43		
649	49.5	709	56.5		
650	50.16	710	56.70		
651	50.70	711	56.86		
652	51.1	712	57.0		
653	51.70	713	57.33		
654	52.16	714	57.73		
655	52.5	715	58.2		
656	52.10	716	58.80		
657	51.63	717	59.13		
658	51.1	718	59.2		
659	51.04	719	59.07		
660	51.03	720	58.83		

Attachment II

Comments Received in Response

to the EPA TECHNICAL REPORT

"Determination of Tire Energy
Dissipation Analysis and
Recommended Practice"

SAE COMMITTEE CORRESPONDENCE

LAND
SEA
AIR
SPACE

Society of Automotive Engineers, Inc.

Committee: Rolling Resistance Subcommittee

Reply To: T.P. Baker
Uniroyal Inc.
6600 E. Jefferson
Detroit, Michigan 48

June 7, 1978

Mr. Charles L. Gray
Acting Director,
Emission Control Technology Division
United States Environmental Protection Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray,

I have reviewed the technical report entitled "Determination of Tire Energy Dissipation-Analysis and Recommended Practices" by Messrs Burgeson and Thompson, which was distributed to the members of the SAE Rolling Resistance Subcommittee at its last meeting, April 26 by Mr. Thompson and yourself. My observations are as follows:

As you know, the SAE has developed a rolling resistance test procedure which is now at the balloting stage in the Highway Tire Committee. It will become an official SAE Recommended Practice within a few months. Glenn Thompson is a member of the Rolling Resistance Subcommittee and as such has helped us develop our procedure.

I am sure that Glenn is aware that the objectives of the technical people who have participated in this endeavor are identical with those stated in the report as EPA objectives, i.e. to obtain test results which are meaningful and valid in what Glenn calls the "real world". Unfortunately, Glenn assumes that the ideal way to achieve these objectives must be "the development of a laboratory test procedure to simulate the 'real world' experience" of the tire. In this respect I think that he is at odds with the rest of the technical community. Simulation is often a good approach, but not necessarily the best one.

I am disturbed by the fact that the report implies that existing test methods are unacceptable and that new ones must be developed. Yet there is no evidence that existing methods, especially the SAE one that Glenn helped us develop, have even been tried by the EPA. How then have they been found unacceptable? If there is evidence to that effect, why has Glenn not brought it to our attention so that we could improve our SAE approach? None of us on the subcommittee wants a method which does not produce meaningful results.

The EPA's primary objective as stated in the report is "to provide public information and guidance on the fuel economy effects of various tires". It seems to me that the credibility of the information provided is of paramount importance. The credibility of the data is enhanced by the adoption of a standardized test procedure which has the public endorsement of the technical community known to be knowledgable on the subject. Therefore for the good of the EPA program and for the greater probability of its public acceptance and success, I recommend that the EPA adopt the tried and proven technology of the SAE Recommended Practice rather than attempt to invent new tests. I believe the EPA objective will be well served by the SAE test and we will all be satisfied with the result.

If on the other hand the EPA uses the SAE method and discovers that the test results do not adequately rank tires for their fuel economy effects, then the EPA will have performed a valuable public service by showing us all that we are on the wrong track and that a better method is needed.

As for the two test procedures described in the appendices of the report, they are innovative and intriguing. I would like to see them used experimentally so that they could be evaluated against existing methods. Further discussion in the absence of data can be little more than speculative comment.

Sincerely,

T P Baker

T.P. Baker
Chairman

/mjb

cc: Rolling Resistance Subcommittee

Engineering Staff
Current Product Engineering
General Motors Corporation

June 6, 1978

Mr. Charles L. Gray
Acting Director
Emission Control Technology Division
U.S. Environmental Protection Agency
Ann Arbor, MI 48105

Dear Mr. Gray:

Attached are my comments you requested on the proposed draft on the "Determination of Tire Energy Dissipation - Analysis and Recommended Practices." We would be pleased to meet with your staff to discuss this in more detail if you should find this desirable.

Sincerely,

Richard C. Moore

Richard C. Moore
Tire-Wheel Systems

/kv
attachment
cc: K. G. Peterson
F. D. Smithson
G. J. Barnes - Environmental Activities Staff
T. Baker - Uniroyal

GENERAL MOTORS RESPONSE TO EPA DRAFT ON "DETERMINATION OF TIRE ENERGY DISSIPATION - ANALYSIS AND RECOMMENDED PRACTICE"

General Motors agrees with the EPA that tire development should be focused toward improved fuel economy for the consumer. We also recognize that in the real world, tires are continually operating in a complex domain of transient conditions. Some of these are temperature, pressure, speed, load, driving, braking, steering, road surface irregularities, and tire wear. The technical challenge upon industry is to improve vehicle fuel economy in general and to meet federal fuel economy standards in particular. Recognizing that tires play a significant role in vehicle fuel economy, then it becomes imperative that test methodologies be established that can effectively assess the principal performance characteristics of tires that relate to vehicle fuel consumption. We don't think that there is a practical way at this time to address all of the real world transient conditions that tires experience. However, steady state tests utilizing free rolling tires have been developed and the resulting data provides good correlation with vehicle fuel economy tests. The success of these correlations lead us to believe that a relatively simple steady state test would provide more meaningful results in the near future than a more complex test procedure.

There are several concerns regarding the proposed EPA tire energy dissipation test procedure. The data resulting from such a test methodology seems to center around the anticipated needs of the EPA and would be of little value to industry for the tire and vehicle design process. As pointed out, the current methods routinely used for assessing rolling resistance seem to be satisfactory for at least obtaining major design improvements in tire rolling resistance performance. The improvements in drive torque and transient effects which are not already suitable reflected from improvements in steady state performance will be addressed when suitable laboratory facilities become available. We are unaware of any instance today where tire improvements based on steady state measuring techniques would be misleading as it relates to road fuel economy.

Some of the additional concerns regarding the proposed procedure are summarized as follows:

- The energy dissipation factor would be expected to have significant variability since it is determined from the difference between two large numbers.

- This would be an additional test for industry since it does not have the general utility needed by vehicle designers to accurately assess effects of design related parameters (load and pressure).

- The preferred test which incorporates both the driven and undriven wheel in combination with the EPA city and highway cycles would require very expensive equipment and would be very time consuming to conduct. There is no evidence that a test of this complexity is technically justified at this time.

- Transient type testing as proposed has many unresolved concerns that need careful investigation. For example, what are test variabilities, data resolution, effect of finned aluminum wheels (high heat transfer), drum and wheel inertias, and speed tolerances.

- The last and principal concern is the implication that steady state measurement methodology will result in misleading information that is directionally wrong for improved fuel economy for the consumer. Since the ability of the proposed procedure to accurately and repeatably rank order tires for their relationship to vehicle fuel economy is unknown, then General Motors recommends that a carefully structured experiment be conducted to demonstrate the effectiveness of each procedure to properly rank order a wide range of tires for their effect on fuel economy. A carefully controlled series of fuel economy tests having repeated measurements on different road schedules and the two EPA laboratory cycles can then be used to confirm the fuel economy - tire energy dissipation/rolling resistance relationship. Analysis of these data will indicate the degree of deficiency that may result from the more simplified current industry practices for evaluating tire performance.

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366 MADISON AVENUE

MOTOR VEHICLE MANUFACTURERS ASSOCIATION
of the United States, Inc.
300 NEW CENTER BUILDING • DETROIT, MICHIGAN 48202 • AREA 313-872-4311

S. E. KNUDSEN, *Chairman*
V. J. ADDUCI, *President and Chief Executive Officer*
THOMAS H. HANNA, *Vice President*

May 31, 1978

Mr. Charles L. Gray
Acting Director
Emission Control Technology
Division
U.S. Environmental Protection
Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray:

The MVMA Ad Hoc Subcommittee on Tire Energy Dissipation has reviewed the draft EPA report entitled "Determination of Tire Energy Dissipation -- Analysis and Recommended Practices". Pursuant to that review, we submit the following comments for your consideration.

MVMA is in general agreement with EPA that tires play a significant role on a vehicle's fuel economy. Also recognized is the importance of focusing future tire development toward improved fuel economy for the consumer. EPA must establish procedures and methodology for determining vehicle fuel economy, and, if these determinations are to be of value, a method of assuring that test components are representative of actual production is important. The industry's role is to furnish test vehicles having components that represent design intent since many components are not yet in full production.

The new concept pursued by EPA, as evidenced by the subject draft, is to quantify certain tires utilized during the vehicle certification process. These data are intended to support the emission certification and fuel economy programs.

It could be used by EPA in two ways: 1) by selecting tires to be used in laboratory fuel economy measurements, or 2) to be used for future reference when vehicle audits are conducted and energy dissipation data are obtained for compliance on production tires.

As stated in the discussion of the subject draft, the reasoning by EPA to have a method "to provide direction, incentive and reward for the production of low energy dissipation tires" has been previously recognized by industry, and a relatively uniform cost effective procedure has been developed by SAE and is out on ballot for approval at the present time.

The approach proposed by EPA to determine a tire's energy dissipation characteristics includes the transient behavior of tires for an arbitrarily selected test cycle. This recommended method would be of little value to industry since it is too specific in nature (only one test load and inflation pressure). It would also be expected to have little resolution capability since it is derived from the difference of two large numbers, both of which are subject to test variability. The approach being pursued by SAE is to initially establish an objective method of quantifying a tire's steady-state performance. The analyzed data thus obtained can readily be interpreted to meet the needs of both vehicle chassis engineers and tire designers. It is believed that the principal tire design changes and vehicle modifications which reduce the steady-state rolling resistance will also result in reductions of energy dissipation during transient conditions. The influence of transient behavior and power transmission can only be properly assessed when suitable laboratory facilities are developed. The EPA has implied, merely by the generation of the subject draft, that current industry practices utilizing steady-state measurement techniques could be misleading. The MVMA is unaware of any instance where the currently obtained steady-state rolling resistance would be misleading as it relates to vehicle fuel economy measurements made on flat roads. One of our principal concerns, however, is the reversal in tire rank order performance that can occur between the flat roadway and the laboratory twin roll facilities where EPA fuel economy is evaluated.

The ability of the proposed procedures to accurately and repeatably rank order tires for their relationship to vehicle fuel economy is unknown. Before any recommended procedure is adopted, the EPA should conduct a program to demonstrate that the test method has the ability to properly rank order a wide range of tires for their effect on fuel economy. This should then be confirmed by a carefully controlled series of road and laboratory fuel economy tests having a suitable number of repeat measurements. This same group of tires should also be quantified using the current industry practices which incorporate steady-state rolling resistance and accurately measured vehicle fuel economy could then be assessed.

Finally, as a general comment, MVMA suggests that, before embarking on an additional complex recommended practice, the need and feasibility for such practice should be clearly demonstrated.

MVMA is grateful for the opportunity to respond to these proposed recommended practices. If you desire to discuss these comments in further detail, please contact me.

Sincerely,

Harry Weaver

Harry B. Weaver, Manager
Environmental Activities Department

HBW/srd

June 20, 1978

Mr. T. P. Baker
Uniroyal Tire Co.
6600 E. Jefferson
Detroit, MI 48232

Dear Tom:

We are writing to you on behalf of Firestone technical personnel in response to the request from EPA for comments on their proposed recommendations for tire energy dissipation tests.

Dr. Schuring has studied the technical content of this EPA report carefully and has no particular quarrels with the explanation of the basic nature of tire losses.

However, we are all in strong disagreement with the proposed test procedures which measure tire properties at other than equilibrium conditions.

Basically, there are known problems with the transient or quasi-steady state test procedures and it seems logical that we should take on thes problems only if the transient tests have been proven to give tire val which are either more repeatable or bear a more direct correlation to actual in-use values than steady-state measurements. Neither of these proofs exists.

The fact that the cycle of operation proposed by EPA represents some particular mode of consumer vehicle operation is not significant with respect to either the question of repeatability or correlation.

Lacking any proven relation with flat road in-use values, neither of the two proposed tests should be accepted in face of their obvious difficulties:

1. Any test of a product or machine operating in a transient conditio is inherently likely to prove less repeatable than a test run with the product or machine in equilibrium condition.

2. Limited data obtained by our company on both a flat-bed tester and on a 62.7" diameter drum indicate a very good correlation between equilibrium and transient tire performance on a relative basis. We know of no data that show that other than equilibrium condition tests show better correlation with the real world. Lacking such proof, there is no satisfactory reason for choosing conditions which are inherently likely to produce less repeatable results.

3. To obtain necessary precision in the proposed EPA transient test, large horizontal forces must be measured and subtracted from one anoth with a precision of less than one pound. This is very difficult, if not impossible, to obtain with any available measurement instruments.

4. The proposed quasi-steady state test would require precise speed control, increased power to drive the test drum, rapid data sampling at fixed time intervals and software for data processing. Such equipment and software would have to be newly developed or acquired.

5. The EPA proposed quasi-steady state procedure requires about 45 minutes for each data point and therefore would require at least 225 minutes to provide the five data points covering three loads and thre pressures to produce the data provided by the currently proposed SAE procedure which obtains the same tire data in just 70 minutes of test time.

6. No test equipment capable of running either of the proposed EPA test procedures is currently available. Design and procurement of such equipment seems unnecessary unless an improvement in results obtained is likely.

We are concerned about the proposed minimum test drum diameter of one meter. It is well known that test drums of very small diameter cause unnatural distortions in the tire tread/belt region which significantl affect tire rolling loss measurements.

We do have data available that show measurements which correlate directly with flat surface measurements can be made on a drum as small as 62.7 inches in diameter but we are not at all sure how far we can go before drum curvature effects become significant. Further researc is required on this point, but for now we believe that a minimum test drum diameter of 1.50 meters should be specified.

We have a minor objection to the statement in the EPA discussion that "during low speed operation the tire is the major source of energy dissipation by the vehicle." The literature supports a conclusion th tires represent only 5% - 10% of vehicle energy dissipation. The vehi engine dissipates something like 80% of the total energy available in the fuel.

We believe the generally sound theoretical reasoning in the EPA presentation does not lead to their conclusions about the proper tire test procedures. We feel we should offer to work with EPA to obtain a data base to prove or disprove the claimed advantages of their two test cycle proposals over the more practical equilibrium test conditio

Since Mr. Thompson quotes Dr. Schuring as an authority in his presentation, we would be glad to have Dr. Schuring's name used in rebuttal. Please work with Dr. Schuring directly if you choose to quote him. We would suggest that he might best be used to provide short technical discussions on specific points which could be submitted as appendices to your committee response.

Very truly yours,

D. J. Schuring
SAE Tire Roll. Resist.
Subcommittee

L. T. Dorsch
SAE Tire Roll.
Resist. Subcom.

K. L. Campbell
SAE Highway
Tire Committee

KLC:np

SAE COMMITTEE CORRESPONDENCE

May 30, 1978

LAND SEA AIR SPACE

Society of Automotive Engineers, Inc.

Committee: Rolling Resistance Subcommittee

Reply To: A. S. Myint
Ford Motor Company
Room 208, Dynamometer
P. O. Box 2053
Dearborn, Mich. 4812

Mr. Charles L. Gray, Active Director
Emission Control Technology Division
U. S. Environmental Protection Agency
Ann Arbor, Michigan 48105

Dear Sir:

I have reviewed the draft of an EPA report "Determination of Tire Energy Dissipation -- Analysis and Recommended Practices" submitted to the subcommittee at the April 26, 1978 meeting and my comments are attached.

Yours truly,

A. S. Myint

rc
cc: T. P. Baker
T. Northrop
Attach.

COMMENTS ON EPA TIRE ROLLING RESISTANCE PROCEDURES

The EPA procedures are intended to give some sort of tire rolling index that is relatable to use in the FTP transient situations. A major question of how this may relate to actual customer use cannot be answered. As the tire warms up, the tire pressure increases (with captive air pressure) and the rolling resistance decreases. This pressure increase is a function of the tire's ability to dissipate heat generated due to rolling losses. Some of the heat is transferred to the road surface and in turn is transferred from the road to the surrounding atmosphere. It is expected that the heat transfer characteristics of a concrete or asphalt highway is different from a small drum in the laboratory. And, again, a flat belt tire machine with a water bearing will have different heat transfer than a steel drum.

This all results in different pressure build-ups (and, therefore, different rolling resistances) for a given tire on different surfaces. This creates the possibility that a tire ranking in the laboratory may not be the same as what it could be if it could be measured on the road under non-equilibrium thermal condition.

The proposed SAE tire rolling resistance procedure is conducted at three different constant pressure levels. These can be related to stabilized road operation since the tire pressures can be measured on the road. The road tire pressure then can be related to rolling resistance that was measured in the laboratory through the pressure/rolling resistance relationship.

The EPA procedure looks at the tire at only one load/tire pressure point. To adequately evaluate a tire, a range of expected load and pressure conditions must be evaluated. If a range of pressures and loads were evaluated, the proposed EPA test procedure would be very time consuming. This is because the tire would have to be "cold soaked" between each load/tire pressure test point. If a test were conducted at 5 load/tire pressure points, the test including soak time would require nearly 24 hours. The time on the tire machine alone would be over 3-1/2 hours.

The data handling equipment required for the procedure defined in Appendix A is generally not available on tire test machines. Some sort of data logger and/or computer system would be required to record data at the specified interval rate between one to five seconds. Also, the system would have to calculate the tire rolling resistance energy requirements.

The tire machine required for the procedure defined in Appendix B does not exist The highly regarded and very elaborate Calspan flat belt tire machine does not have the capability to run this procedure.

The SAE proposed tire rolling resistance procedure evaluates at five load/tire pressure hot stabilized conditions. This procedure can be started with a cold tire. The rolling resistance of the tire could be observed during warm-up in the SAE procedure with no additional test time and this would provide some insight into "cold" tire rolling resistance.

In summary, the proposed EPA test procedures are overly complex and in the long run may not adequately meet the goals of the EPA. It is suggested that the proposed SAE procedure with monitoring of rolling resistance during warm-up be used for EPA's needs so that tire rolling resistance in non-thermal and thermal equilibrium conditions can be determined. From this learning process future direction for tire rolling resistance testing can be determined intelligently.