SAE International

SURFACE VEHICLE RECOMMENDED PRACTICE

SAE J2562

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Biaxial Wheel Fatigue Test

Foreword

This wheel fatigue test simulates wheel road loads by applying variable radial and lateral loads through a tire and wheel assembly. The scaleable test load sequence is developed for individual wheels based on data obtained while running established vehicle durability schedules.

1. Scope

This SAE Recommended Practice provides uniform laboratory procedures for biaxial fatigue testing of wheels intended for normal highway use and temporary use on passenger car vehicles and light trucks. The appendices provide scaleable load files that are applicable to ballasted passenger cars and ballasted light trucks. A load file for unballasted passenger cars will be added to this document.

1.1 Rationale Statement

Revisions to this document include: re-wording of the scope to include ballasted light trucks; renumbering of Appendix A to follow SAE guidelines; increases in Appendix A, Table 1 outboard load factors $K_{R,O}$ and $K_{L,O}$ (analytical review during writing of SAE Paper 2004-01-1578 identified the need to increase the scale factors); and addition of Appendix B: SAE Biaxial Load Sequence for Ballasted Light Trucks.

2. References

2.1 Applicable Documents

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

2.1.1 SAE PUBLICATIONS

Available from Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1982—Nomenclature—Wheels for Passenger Cars, Light Trucks and Multi-Purpose Vehicles

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2.1.2 INTERNATIONAL STANDARDS ORGANIZATION PUBLICATIONS

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002.

ISO 3911—Wheel/rims—Nomenclature, designation, marking and units of measurement

2.1.3 TIRE AND RIM ASSOCIATION INC. YEAR BOOK PUBLICATIONS

Available from Tire and Rim Association Inc., 175 Montrose West Ave., Suite 150, Copley, OH 44321.

The Tire and Rim Association Inc., Year Book.

2.2 Related Publications

The following publications are provided for informational purposes only and are not a required part of this document.

2.2.1 SAE PUBLICATIONS

Available from Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE 830135—Automotive Wheels, Method and Procedure for Optimal Design and Testing; V. Grubisic and Gerard Fischer
SAE 841705—Cast Aluminum Wheels for Trucks and Buses—Testing and Evaluation; V. Grubisic and Gerhard Fischer
SAE 841706—Design Optimization of Forged Wheel Hubs for Commercial Vehicles; V. Grubisic, Gerhard Fischer, Manfred Heinritz
SAE 982840—Design Criteria and Durability Approval of Wheel Hubs; V. Grubisic, Gerhard Fischer
SAE 1999-01-0781—Proof of Wheel Fasteners by Multiaxial Tests in the Biaxial Wheel Test Rig; Gerhard Fischer, V. Grubisic, Werner Hasenmaier.

2.2.2 FRAUNHOFER INSTITUT BETRIEBSFESTIGKET (LBF) BIAXIAL WHEEL/HUB TEST FACILITY PROCEEDINGS OF THE 5TH INTERNATIONAL USER MEETING 13 SEPTEMBER 2001, DARMSTADT, GERMANY

Available from Fraunhofer Institut für Betriebsfestigkeit (LBF), Bartningstrasse 47, Darmstadt D-64289, Germany.

Numerical Estimation of Tilt Angle for Load Program Testing; Roland Eisenkolb, Dr. Heinz Schwendemann

3. Definitions

3.1 Biaxial Test Machine

A machine for evaluating the fatigue life of the wheel under combined radial and lateral loads applied to a rotating tire-wheel assembly through the tire.

3.2 Curb

A radially inward extension of the drum designed to contact the tire sidewall for reaction of lateral load.

3.3 Test Load Sequence

A series of "block cycle" radial and lateral loads, tilt angles, wheel revolutions, and drum speed combinations that correlate to specific vehicle road load occurrences.

3.4 Tire Contact Patch Loads

Orthogonal radial, lateral and fore-aft wheel plane loads that act at the center of the interface between the tire and road surface.

3.5 Rated Wheel Load

Design load for wheel as specified by manufacturer equal to 1/2 the maximum static front axle load.

3.6 Radial Test Load

Radial load applied by test machine through the tire contact patch.

3.7 Lateral Test Load

Lateral load applied by test machine through the tire sidewall adjacent to the tire contact patch.

3.8 Radial Base Load

Radial wheel load that must be scaled for vehicle application and design load.

3.9 Lateral Base Load

Lateral wheel load that must be scaled for vehicle application and design load.

3.10 Tilt Angle

Wheel camber angle when inside biaxial test machine drum (inboard lateral loads use negative tilt angles).

3.11 Inboard Load

Lateral load vector acting at the tire contact patch toward the vehicle. This is the lateral load the tire-wheel assembly experiences when it is on the outside of a turn.

3.12 Outboard Load

Lateral load vector acting at the tire contact patch away from the vehicle. This is the lateral load the tire-wheel assembly experiences when it is on the inside of a turn.

3.13 Zero lateral load

Lateral load when the tire-wheel assembly is driven straight (no cornering or toe).

4. Symbols

4.1 $F_{L,B}$ = Lateral Base Load (N)

4.2 $F_{L,T}$ = Lateral Test Load (N)

4.3 $F_{R,B}$ = Radial Base Load (N)

4.4 $F_{R,T}$ = Radial Test Load (N)

4.5 F_{W} = Rated Wheel Load (N)

4.6 $K_{L,i}$ = Lateral Inboard Load Scale Factor

4.7 $K_{L.o}$ = Lateral Outboard Load Scale Factor

4.8 $K_{L.z}$ = Lateral Zero Load Scale Factor

4.9 $K_{R.i}$ = Radial Inboard Load Scale Factor

4.10 $K_{R.o}$ = Radial Outboard Load Scale Factor

4.11 $K_{R.z}$ = Radial Zero Lateral Load Scale Factor

4.12 θ = Tilt Angle (Degrees)

5. Test Requirements

5.1 Equipment

5.1.1 BIAXIAL FATIGUE TEST MACHINE

5.1.1.1 Cantilevered, internal drum (see Figures 1 and 2) with inboard and outboard curbs as detailed in Figure 3. The tire outside diameter is recommended to be within 50% to 80% of the drum internal diameter for wheel stress reproduction.

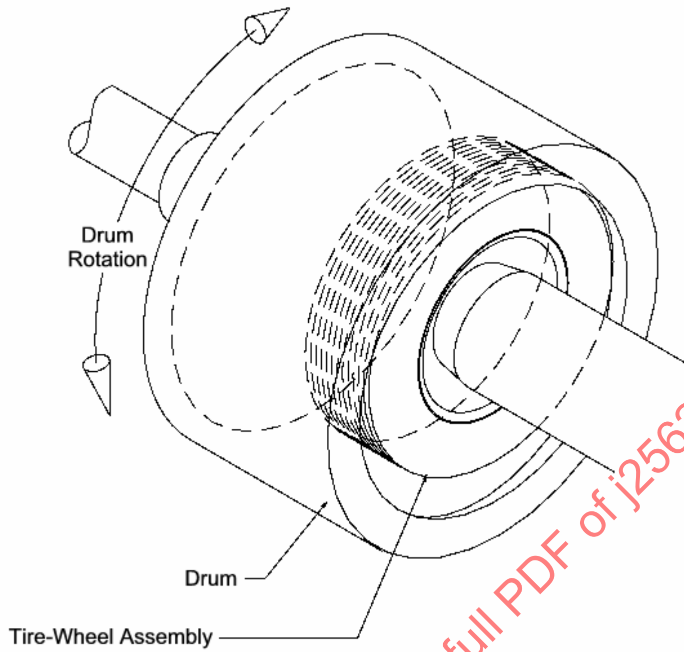

FIGURE 1—INTERNAL DRUM

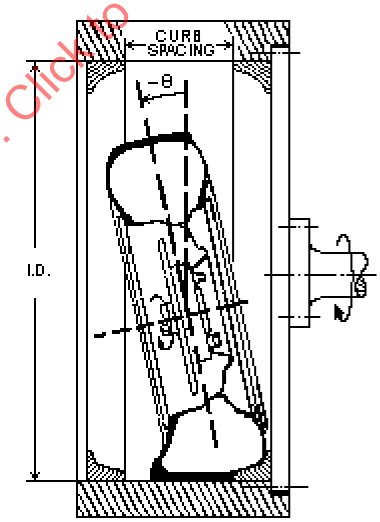

FIGURE 2—DETAIL CROSS-SECTION OF TYPICAL TIRE-WHEEL ASSEMBLY INSIDE DRUM WITH INBOARD LATERAL LOAD

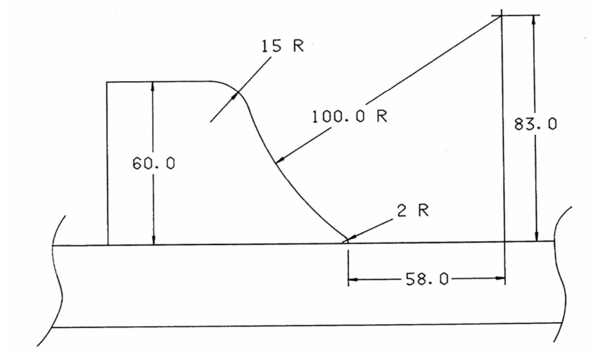

FIGURE 3—DETAIL CROSS-SECTION OF TYPICAL DRUM INBOARD AND OUTBOARD CURB

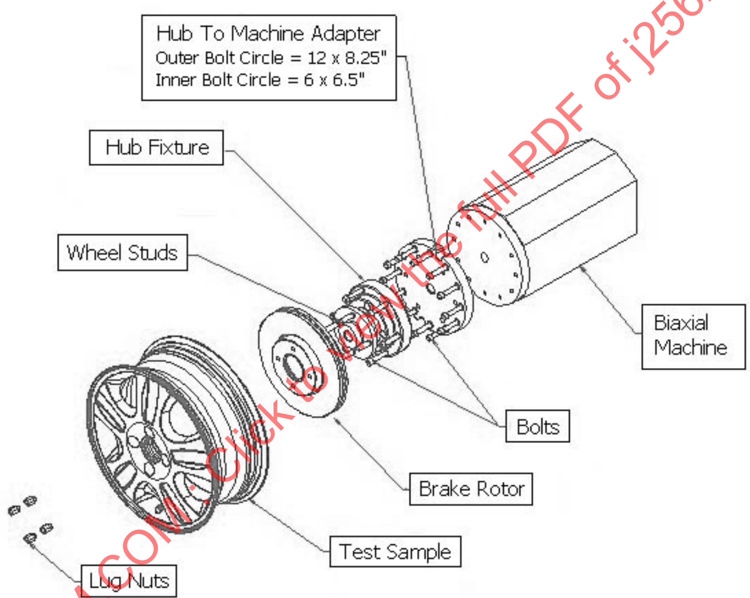

FIGURE 4—TYPICAL WHEEL, BRAKE ROTOR, WHEEL BEARING, ADAPTER, AND LOAD SPINDLE ASSEMBLY

5.1.1.2 A steering knuckle-wheel bearing-brake assembly can be used to support test pieces.

NOTE—This procedure is not intended to test a steering knuckle when it is used for test piece support.

5.1.1.3 A wheel bearing hub adapter can be used to support test pieces when a complete steering knuckle is not used to support test pieces (see Figure 4).

5.1.1.4 A load spindle with a wheel adapter plate with specified stud sizes and bolt patterns is used to support test pieces when a wheel bearing hub is not used to support test pieces.

5.1.1.5 Flat wear plates or brake rotors may be mounted between the wheel and the adapter to provide a replaceable, smooth, clean surface.

5.1.1.6 *Type A Biaxial Test Machine, Figure 5.*

With this machine the load cells and actuators are orthogonal to the drum surface. The tilt (camber) angle is not actively controlled but is controlled with a fixed linkage. As the lateral actuator load is increased the camber angle is increased a proportional amount. Mathematical equations are required to relate actuator loads to wheel loads. The tilt axis passes through the wheel center.

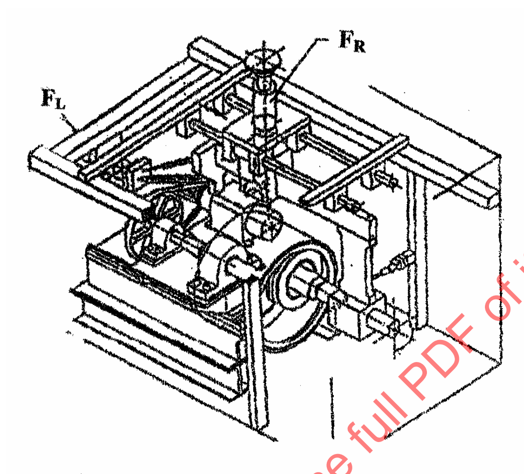

FIGURE 5—TYPE A BIAXIAL TEST MACHINE

5.1.1.7 *Type B Biaxial Test Machine, Figure 6.*

With this machine the actuators and load cells are orthogonal with the drum surface and the tilt angle (camber) is infinitely adjustable. The tilt axis does not pass through the wheel center. A mathematical formula must be used to relate the actuator loads to the wheel loads.

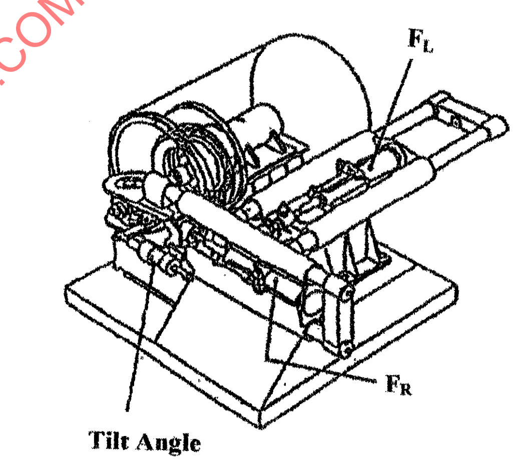

FIGURE 6—TYPE B BIAXIAL TEST MACHINE

5.1.1.8 Type C Biaxial Test Machine, Figure 7.

With this machine radial and lateral load cells are always orthogonal to the wheel giving a direct measurement of wheel radial and lateral loads. The tilt (camber) axis passes through the wheel center and the angle is infinitely adjustable.

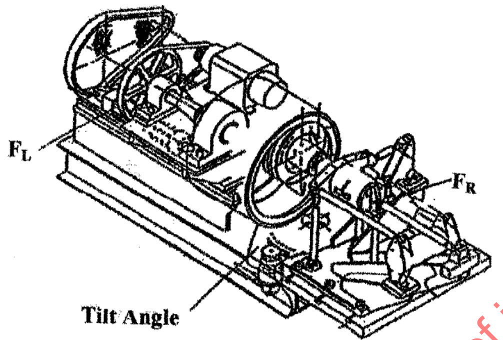

FIGURE 7—TYPE C BIAXIAL TEST MACHINE

5.2 Test Program

5.2.1 Input the scaled SAE Biaxial Load Sequence in Appendix A into the Biaxial Test Machine. The load sequence will contain the following for each radial, lateral test load combination:

a) Radial Test Load ($F_{R,T}$)
b) Lateral Test Load ($F_{L,T}$ where inboard direction is +)
c) Tilt Angle (outboard tilt + θ)

NOTE—Inboard lateral loads typically require negative tilt angles (see Figure 2).
NOTE—Type A machine load sequences do not require tilt angle values.

d) Wheel Revolutions
e) Drum Speed (rpm)

5.3 Biaxial Test Machine Mechanical Setup

5.3.1 Adjust distance between curbs (see curb spacing in Figure 2) inside the drum to allow the inflated tire to fit between the curbs without rubbing against the tire sidewall at the highest load condition. Also, curb separation should prevent touching both curbs during extreme tilt angles.

5.3.2 For the Type A and C machines, adjust the wheel spindle position so that the non-tilted wheel and tire assembly is midway between the curbs and positioned for the desired rolling radius.

5.3.3 Install the adapters necessary for the attachment of the required test components as described in 5.1.1.

5.4 Installation of Test Components

5.4.1 Test wheels should be installed on the adapter plate using representative production fasteners as specified by the vehicle manufacturer.

5.4.2 Using a star pattern, tighten the wheel nuts or bolts to the minimum torque specified by the vehicle manufacturer or as otherwise specified. Repeat tightening star pattern until torque values stabilize.

5.4.3 Inflate tire to pressure specified by test requester. Recommended tire inflation pressures for P Type passenger car tires are 200 kPa (29 psi), 400 kPa (58 psi), or the vehicle application pressure. Recommended tire inflation pressures LT Type truck tires are 448 kPa (65 psi), or 1.2 times the usage pressure but not less than 448 kPa (65 psi) or the vehicle application pressure. Recommended tire inflation pressures for T Type temporary use passenger car tires are 420 kPa (60 psi), or the vehicle application pressure.

NOTE—For the Type B and C machines, the same tire inflation pressure should be used for both test load development (establishing tilt angles for each radial and lateral load pair) and for testing.

5.5 Biaxial Test Machine Operation

5.5.1 Position the test assembly in the drum.

5.5.2 Apply a nominal radial load to the tire-wheel assembly; suggested load of 500 N.

5.5.3 Begin drum rotation.

5.5.4 Apply the SAE Biaxial Load Sequence. Minimize unaccounted fatigue cycles by limiting the transition time between speed and load changes to 5 seconds or less.

5.5.5 Periodically check test pieces for fastener loosening or fatigue cracks.

5.6 Inspection

5.6.1 The test pieces are to be inspected at the end of test and at other intervals as specified by test requester.

5.6.2 Record test sequence number and wheel revolutions.

5.6.3 It may be necessary to remove test components to inspect for cracks.

5.6.4 If test is to be continued, reinstall the test components per section 5.4 and continue testing.

6. Performance Status Classification

6.1 Test Termination

6.1.1 Completion of wheel revolution count under test loads as specified by test requester.

6.2 Early Test Termination—Test Termination Prior to Completion of Wheel Revolution Count

6.2.1 Loss of tire pressure resulting from a fatigue crack.

6.2.2 The inability of the test assembly to sustain load.

6.2.3 Development of a propagating fatigue crack through a section observable from both sides of wheel.

NOTE—Whenever one or more wheel fastener breaks on test it is recommended that all wheel fasteners should be replaced.

NOTE—Failure of the test tire or other parts of the test fixture do not require test termination unless it results in damage to the test components, in which case the test becomes invalid. Test tires may be replaced and the wheel test continued.

7. Performance Requirements

No performance requirements have been established for this procedure.

8. Notes

8.1 Key Words

Wheel, Fatigue, Biaxial

8.2 Marginal Indicia

The change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

PREPARED BY THE SAE BIAXIAL WHEEL FATIGUE LAB TEST TASK FORCE
OF THE SAE WHEEL STANDARDS COMMITTEE

APPENDIX A
SAE BIAXIAL LOAD SEQUENCE FOR BALLASTED PASSENGER VEHICLES

A.1 Biaxial Wheel Tests are conducted by repeatedly applying load sequences of radial and lateral load pairs to a rotating tire-wheel assembly. Each load pair and its respective tilt angle are applied for the number of specified wheel revolutions and then the control system steps to the next load pair in the load sequence. This appendix contains the recommended load sequences for ballasted passenger vehicles. Due to the mechanical limitations of all three test machine types, the load sequences are divided into two sequences; 1) high speed sequence for load pairs that are applied for many wheel revolutions; and 2) medium speed sequence for load pairs that are applied for few wheel revolutions. It is necessary to use both the high speed and the medium speed load sequences to make one test. Table A4 lists the unique load pairs for both the high speed and medium speed sequences.

A.1.1 Scaling Base Load Sequence to Get Test Load Sequence

A.1.1.1 Both the high speed base load sequence in Table A2 and the medium speed base load sequence in Table A3 must be scaled according to the design load of the wheel using the application factors listed in Table A1. The following calculations must be done for each base load pair in Table A2 and Table A3.

A.1.1.1.1 Calculate test loads $F_{R,T}$ and $F_{L,T}$ using equations A1 and A2 when lateral base load $F_{L,B}$ is inboard (positive) where

$$F_{R,T} = \frac{F_{R,B} \cdot F_W}{K_{R,i}} \tag{Eq. A1}$$

$$F_{L,T} = \frac{F_{L,B} \cdot F_W}{K_{L,i}} \tag{Eq. A2}$$

A.1.1.1.2 Calculate test loads $F_{R,T}$ and $F_{L,T}$ using equations A3 and A4 when lateral base load $F_{L,B}$ is outboard (negative) where*:*

$$F_{R,T} = \frac{F_{R,B} \cdot F_W}{K_{R,o}} \tag{Eq. A3}$$

$$F_{L,T} = \frac{F_{L,B} \cdot F_W}{K_{L,o}} \tag{Eq. A4}$$

A.1.1.1.3 Calculate test loads $F_{R,T}$ and $F_{L,T}$ using equations A5 and A6 when lateral base load $F_{L,B}$ is zero where*:*

$$F_{R,T} = \frac{F_{R,B} \cdot F_W}{K_{R,z}} \quad \text{(Eq. A5)}$$

$$F_{L,T} = \frac{F_{L,B} \cdot F_W}{K_{L,z}} \quad \text{(Eq. A6)}$$

TABLE A1—LOAD SCALE FACTORS FOR VEHICLE APPLICATION

Vehicle Application	Load Scale Factors		
Ballasted Passenger	When Lateral Loads are Inboard (+)	When Lateral Loads are Outboard (-)	When Lateral Loads are Outboard Zero
Radial Loads	$K_{R.i}$ = 5729	$K_{R.o}$ = 6429	$K_{R.z}$ = 6000
Lateral Loads	$K_{L.i}$ = 6153	$K_{L.o}$ = 9214	$K_{L.z}$ = 1

TABLE A2—HIGH SPEED BASE LOAD SEQUENCE FOR BALLASTED PASSENGER VEHICLES (RECOMMENDED DRUM SPEED OF 750 rpm)

Load Step	$F_{R,B}$ Radial Base Load (N)	$F_{L,B}$ Lateral Base Load (N)	Wheel Revolutions	Load Step	$F_{R,B}$ Radial Base Load (N)	$F_{L,B}$ Lateral Base Load (N)	Wheel Revolutions
1	7000	2250	311	49	11000	1000	304
2	11000	0	330	50	3000	500	262
3	11000	1000	304	51	7000	2250	311
4	9000	1250	317	52	9000	1250	317
5	6000	3250	283	53	7000	2250	311
6	8000	-2000	113	54	11000	0	330
7	9000	2250	320	55	9000	1250	317
8	12000	-1250	341	56	7000	2250	311
9	9000	1250	317	57	11000	0	330
10	11000	0	330	58	11000	1000	304
11	8000	-3750	326	59	7000	2250	311
12	9000	3750	262	60	11000	0	330
13	7000	2250	311	61	9000	2250	320
14	11000	1000	304	62	15000	-250	283
15	9000	2250	320	63	11000	1000	304
16	9000	1250	317	64	6000	3250	283
17	7000	2250	311	65	7000	2250	311
18	9000	1250	317	66	11000	0	330
19	9000	2250	320	67	11000	1000	304
20	9000	1250	317	68	11000	0	330
21	13000	-250	324	69	9000	2250	320
22	13000	2500	136	70	7000	2250	311
23	13000	-250	324	71	6000	3250	283
24	7000	-4250	261	72	7000	2250	311
25	11000	0	330	73	9000	1250	317
26	9000	2250	320	74	13000	-250	324
27	7000	2250	311	75	9000	1250	317
28	13000	1250	341	76	7000	2250	311
29	9000	2250	320	77	9000	2250	320
30	6000	3250	283	78	14000	250	127
31	9000	1250	317	79	7000	2250	311
32	11000	0	330	80	9000	2250	320
33	8000	-1000	311	81	7000	2250	311
34	9000	1250	317	82	11000	1000	304
35	11000	0	330	83	7000	2250	311
36	13000	1250	341	84	4000	1500	428
37	11000	0	330	85	13000	-250	324
38	9000	1250	317	86	12000	-1250	341
39	13000	1250	341	87	7000	2250	311
40	9000	1250	317	88	11000	1000	304
41	9000	2250	320	89	13000	-250	324
42	11000	0	330	90	7000	2250	311
43	9000	1250	317	91	13000	-250	324
44	8000	-1000	311	92	7000	2250	311
45	9000	1250	317	93	13000	-250	324
46	9000	2250	320	94	3000	500	262
47	7000	2250	311	95	13000	-250	324
48	2000	-1750	171	96	8000	-1000	311

TABLE A3—MEDIUM SPEED BASE LOAD SEQUENCE FOR BALLASTED PASSENGER VEHICLES (RECOMMENDED DRUM SPEED OF 400 rpm)

Load Step	$F_{R,B}$ Radial Base Load (N)	$F_{L,B}$ Lateral Base Load (N)	Wheel Revolutions
1	11000	-2500	67
2	11000	2250	156
3	6000	4500	177
4	7000	5500	184
5	6000	4500	177
6	7000	5500	184
7	18000	-750	152
8	7000	5500	184
9	11000	2250	156
10	18000	-2000	29
11	4000	2250	180
12	18000	-750	152
13	8000	6500	73
14	4000	2250	180
15	11000	2250	156
16	20000	-2000	49
17	16000	750	206
18	5000	-4500	58
19	6000	4500	177
20	15000	-2000	55
21	16000	750	206
22	6000	4500	177
23	18000	500	23
24	11000	2250	156
25	15000	1750	24
26	6000	4500	177
27	11000	2250	156
28	11000	3500	54
29	9000	7500	32
30	20000	-750	124

TABLE A4—BALLASTED PASSENGER VEHICLE LOADS UNIQUE BASE LOAD PAIRS FOR EACH SPEED FILE

High Speed Base Load Pairs				Medium Speed Base Load Pairs		
Load Pair	$F_{R,B}$ Radial Load (N)	$F_{L,B}$ Lateral Load N		Load Pair	$F_{R,B}$ Radial Load (N)	$F_{L,B}$ Lateral Load (N)
HA	9000	3750		MA	9000	7500
HB	6000	3250		MB	8000	6500
HC	13000	2500		MC	7000	5500
HD	7000	2250		MD	6000	4500
HE	9000	2250		ME	11000	3500
HF	4000	1500		MF	4000	2250
HG	9000	1250		MG	11000	2250
HH	13000	1250		MH	15000	1750
HJ	11000	1000		MJ	16000	750
HK	3000	500		MK	18000	500
HL	14000	250		ML	18000	-750
HM	11000	0		MM	20000	-750
HN	13000	-250		MN	15000	-2000
HP	15000	-250		MP	18000	-2000
HQ	8000	-1000		MQ	20000	-2000
HR	12000	-1250		MR	11000	-2500
HS	2000	-1750		MS	5000	-4500
HT	8000	-2000				
HU	8000	-3750				
HV	7000	-4250				

A.1.1.1.4 Repeat High Speed Load Sequence of test loads eight times for each one application of the Medium Speed Load Sequence.

A.1.2 Determine Tilt Angles for Each Load Pair in Test Load Sequence for a Specific Tire Size and Tire Inflation Pressure

A.1.2.1 Type A Machine does not control the tilt angle. No tilt angle values are required.

A.1.2.2 Type B and C Machines must be given a specific tilt angle for each unique load pair in the test sequence. There are three accepted methods for establishing tilt angles. Any appropriate method may be used.

A.1.2.2.1 Tilt Angle Determination Method 1

Mount tire-wheel combination representative of test components on Type A machine, apply all unique test load pairs and record tilt angles for each load pair. Input these tilt angles into test load sequence.

A.1.2.2.2 Tilt Angle Determination Method 2

Strain gage a wheel, load the wheel on a force/moment tire test machine or equivalent fixture and record strains for each load pair. Then put same wheel on Type B or C machine and actively change tilt angle to minimize difference in wheel strains from biaxial machine and wheel strains from force/moment machine. For a Type B machine, loads given in the wheel coordinate system must be transformed into actuator loads in the machine coordinate system using the kinematics of the machine linkage as a function of the tilt angle (see section 5.1.1.7). So for Type B machines it is necessary to change not only the tilt angle but also the actuator loads by this coordinate transformation. Type C machines do not require this wheel loads to actuator loads coordinate transformation. Perform wheel tests using the tilt angle that produced the minimum difference in wheel strain values for each unique load pair in Table 4.

A.1.2.2.3 Tilt Angle Determination Method 3

(Force/Moment equilibrium technique): For each unique load pair in the test load sequence, determine the location of the resultant load vector and change the tilt angle until the resultant load vector passes through the tire-to-road contact patch as by driving. This point is located approximately on the radial centerline of the rim at the radial distance equal to the rolling radius of the tire from the center of the wheel. A procedure for determining of the resultant load vector in a biaxial test machine and for a closed loop control of the tilt angle is given by International Patent application PCT WO 01/71307 A1 (application date 21 March 2001).

APPENDIX B
SAE BIAXIAL LOAD SEQUENCE FOR BALLASTED LIGHT TRUCKS

B.1 Biaxial Wheel Tests are conducted by repeatedly applying load sequences of radial and lateral load pairs to a rotating tire-wheel assembly. Each load pair and its respective tilt angle are applied for the number of specified wheel revolutions and then the control system steps to the next load pair in the load sequence. This appendix contains the recommended load sequences for ballasted light trucks. Due to the mechanical limitations of all three test machine types, the load sequences are divided into two sequences; 1) high speed sequence for load pairs that are applied for many wheel revolutions; and 2) medium speed sequence for load pairs that are applied for few wheel revolutions. It is necessary to use both the high speed and the medium speed load sequences to make one test. Table B4 lists the unique load pairs for both the high speed and medium speed sequences.

B.1.1 Scaling Base Load Sequence to Get Test Load Sequence

B.1.1.1 Both the high speed base load sequence in Table B2 and the medium speed base load sequence in Table B3 must be scaled according to the design load of the wheel using the application factors listed in Table B1. The following calculations must be done for each base load pair in Table B2 and Table B3.

B.1.1.1.1 Calculate test loads $F_{R,T}$ and $F_{L,T}$ using equations B1 and B2 when lateral base load $F_{L,B}$ is inboard (positive) where

$$F_{R,T} = \frac{F_{R,B} \cdot F_W}{K_{R,i}} \quad \text{(Eq. B1)}$$

$$F_{L,T} = \frac{F_{L,B} \cdot F_W}{K_{L,i}} \quad \text{(Eq. B2)}$$

B.1.1.1.2 Calculate test loads $F_{R,T}$ and $F_{L,T}$ using equations B3 and B4 when lateral base load $F_{L,B}$ is outboard (negative) where:

$$F_{R,T} = \frac{F_{R,B} \cdot F_W}{K_{R,o}} \quad \text{(Eq. B3)}$$

$$F_{L,T} = \frac{F_{L,B} \cdot F_W}{K_{L,o}} \quad \text{(Eq. B4)}$$