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Do Changes in Temperature and Inflation Pressure Affect Rolling Resistance During Road and Track Testing for Fuel Economy of Class 8 Tractor-Trailers?

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Abstract

Data from air cavity thermistors, tire pressure monitoring systems (TPMS), and SAE J1269 rolling resistance tests were analyzed to evaluate the significance of changes in tire pressure on rolling resistance during fuel economy tests of class 8 tractor trailers.

Thermistor data show that air cavity temperatures vary, with the main increase happening during the warm-up run, and measurable cooling during the fuel measurement breaks between runs. Inflation pressure also increases by 50 - 70 kPa during the warm-up run, but once the tire has warmed up, the pressure is more stable, rarely varying by more than 20 kPa during a test run.

Results of SAE J1269 rolling resistance tests allow estimation of rolling resistance force for any specified load and inflation pressure. Using the test weight of the truck, rolling resistance force was estimated for inflation pressures ranging from 550 to 860 kPa. The relationship between the inflation pressure and rolling resistance was roughly linear. The relationship was then used to estimate changes in fuel consumption due to changes in inflation pressure normalized to the cold inflation pressure. For each change of relative inflation pressure of 5%, rolling resistance would change by about 1%. Using a common return factor of a 1% change in fuel consumption for every 5% change in rolling resistance, a change in relative inflation pressure of 5% would result in a change of fuel consumption of about 0.2%. The precision of the J1321 fuel economy tests was measured to be plus or minus about 1%. This suggests that the warm-up run provided for in the test method stabilizes the tire pressure and rolling resistance, and that interference due to changes in rolling resistance during a test run or between runs is a concern only for tests that measure small changes in fuel consumption. While the results obtained here are used to assess the effect of inflation pressure on the SAE J1321 test and only apply to the particular tires tested, the method of analysis may be useful in the assessment of the effect of over- or underinflated tires on fuel consumption in the wider long-haul trucking fleet.

Keywords

Rolling resistance; inflation pressure; road tests; SAE J1269 test; SAE J1321 test

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Introduction

The U.S. Environmental Protection Agency (EPA) has been testing the performance of low rolling resistance tires and aerodynamic fairings in order to evaluate their potential to reduce fuel consumption and emissions of greenhouse gas and criteria pollutants [1,2,3]. Tests have been conducted using the SAE J1321 test method [4]. It is a well-known fact that as tires heat up during initial use, rolling resistance decreases due to decreased energy dissipation by elastomers and increased inflation pressure [5,6]. The test method thus specifies that the test vehicles be warmed up for at least an hour to stabilize rolling resistance before testing is done. A warm up is also needed to ensure that lubricants and other vehicle components have stabilized, thus minimizing extraneous sources of variability in the test results. Because decreased rolling resistance results in decreased fuel consumption [3], changes in inflation pressure due to heating of tires could interfere with the results of a fuel consumption tests such as the SAE J1321. However, little has been published about the magnitude of inflation pressure changes during such tests and the resulting effects on fuel consumption, particularly for modern trucks and tires.

During recent track and tire testing, EPA monitored the magnitude of the changes in air cavity temperature and inflation pressure during track tests and analyzed the relation between inflation pressure and rolling resistance. Those data are combined with previous EPA analyses on the relation between rolling resistance and fuel consumption [3] to provide a quantitative estimate of the potential for interference to the SAE J1321 test by changes in tire inflation pressure.

Methods

Air cavity temperature and inflation pressure was measured as part of track tests conducted for EPA by the Southwest Research Institute at the Pecos Research and Testing Center in Pecos, Texas. A sample of the tires used on the test truck was tested for rolling resistance using the SAE J1269 test method at the Smithers-Rapra laboratory in Ravenna, Ohio.

Track tests

Track tests were conducted in July, 2015 as part of an evaluation of fuel economy improvements generated by various aerodynamic devices. The test truck for which inflation pressure was measured was the control truck being used for the SAE J1321 test and has the same specifications as the trucks used by EPA to evaluate the relation between rolling resistance and fuel consumption in an earlier test [3]. This truck as a 2012 class 8 Freightliner Cascadia model 125 with a Detroit DD15 engine. The transmission was a Fuller model FRO-152109C 10 speed, with a Rockwell model MT40-14X rear axle that had a 3.36 gear ratio. The trailer was a Wabash 53-foot (16 meter) box trailer. The trailer was ballasted to provide a gross vehicle weight of 29,800 kg. Load was distributed over the axles as follows: Steer, 5,370 kg, or 18%; Drive, 12,140 kg or 41%, Trailer, 12,290 kg or 41%.

Fuel consumption was measured by weighing a detachable fuel tank. Tire pressure and air cavity temperature were measured in situ for all tires by a Valor Tire Pressure Monitoring System (TPMS) recorded by a Campbell data recorder. Although sensors were installed on

all 18 tires, data are not available for all the tires in every test due to occasional sensor malfunctions. Air cavity temperature can be considered a surrogate for the temperature of the actual tire rubber, although the relation between the two is not known for the tires tested.

The test course is a circular track approximately 13 km (8 mi) in circumference. The warm-up runs lasted for about one hour at a constant speed of 100 km/hr, (62 mi/hr) for a total distance of 100 km (62 mi). Test runs lasted about 50 minutes at a constant speed of 100 km/hr, for a total distance of about 80 km (50 mi) per run. The time between the warm-up and test runs and between the test runs when the trucks were parked to allow the fuel to be weighed was up to 20 minutes, but was usually around 10 minutes. Ambient temperature during the tests ranged from 25° to 38° C (77 – 100° F). The cold inflation pressure at the start of the test was 690 kPa (100 psi) for the drive and trailer tires and 760 kPa (110 psi) for the steer tires. The cold inflation pressure was set in the morning before the test, when the ambient temperature was about 25° C (77° F).

Tire tests

A sample of nine tires (three for each axle position) of the type used on the test truck were tested for rolling resistance using the SAE J1269 test method [7] and the ISO28580 test method [8]. The SAE J1269 method involves rotating the tire at 80 km/hr (50 mi/hr) against a 1.7 m (67 inch) road wheel with an 80 grit surface. The tire is subjected to a specified range of loads, and the rolling resistance determined by the force method. Tires are warmed up on the road wheel to ensure that the test is conducted in thermal equilibrium. Rolling resistance is measured for 5 test points, with regulated inflation pressures ranging from 532 kPa (77 psi) to 914kPa (132 psi) and loads ranging from 6,312 N (643 kg) to 25,252 N (2,574 kg). Table 1 provides a summary of the tires tested and some of their characteristics, including the rolling resistance results from the ISO 28580 test [8], a single point test used by EPA to verify low rolling resistance tires under the SmartWay Technology program.

Results from the SAE J1269 test points are used to calculate the coefficients of a multivariate non-linear regression model that can be used to calculate and estimate rolling resistance force at any desired combination of load and inflation pressure:

$$F_r = A_0 + A_1 F_z + A_2 \frac{F_z}{P} + A_3 \frac{F_z^2}{P} \quad (1)$$

Where F_r is the rolling resistance force,

A_0 , A_1 , A_2 , and A_3 are the coefficients calculated by the regression analysis

F_z is the load on the tire, and

P is the inflation pressure.

The relation between the inflation pressure and load was calculated by establishing 8 inflation pressure conditions surrounding the cold inflation pressures of 690 kPa (100 psi) for drive and trailer and 760 kPa (110 psi) for steer set during the track tests. Inflation

pressures ranged from 552 kPa (80 psi) for drive and trailer, 621 kPa (90 psi) for steer to 792 kPa (115 psi) for driver and trailer, 862 kPa (125 psi) for steer. Loads were based on the axle weight distribution of the truck used in the track test: Steer at 52,493 N (5,370 kg), drive at 118,799 N (12,140 kg), and trailer at 120,266 N (12,290 kg). Because there are two tires on the steer axle, 8 tires on the drive axles, and another 8 tires on the trailer axles, the load per tire used in the regression analysis is 26,289 N (2,681 kg) for steer, 14,848 N (1,514 kg) for drive, and 15,033 N (1,532 kg) for trailer.

Results

Changes in inflation pressure during track tests

TPMS and air cavity temperature data clearly show that as a cold tire heats up, the inflation pressure increases with a roughly linear relationship (Figure 1). However, the scatter in the data suggest that some unknown source of error is affecting the observed relationship. This could affect the pattern of changes in air cavity temperature and inflation pressure during the tests.

This is demonstrated by a comparison of the changes in air cavity temperature in the tire during a series of test runs (Figure 2) with the changes in inflation pressure during the same series of test runs (Figure 3). The particular data shown in Figures 2 and 3 are for the steer tire on the driver's side, although examination of other tires in different axle positions shows similar results. In Figure 2, the temperature increases very rapidly through the warmup run, increasing by about 25 degrees and starting to stabilize at about 53° C (127 °F). During the breaks between the test runs, the air in the tire cools off, by about 3 to 5 degrees and then increases by another 5 to 10 degrees during the next test run, with a final temperature at the end of all of the test runs of about 63° C (145° F). It appears clear, that although the tire is well warmed up during the test, it does not achieve thermal equilibrium. It should also be noted that the ambient temperature rose during the test period, from 27° (80° F) at the start of the first test to 36° (97° F) by the end of the last test, and this change in ambient temperature may have been one reason why the air cavity temperatures never achieved thermal equilibrium.

Despite this lack of thermal equilibrium, the inflation pressure appears to stabilize during the warm-up run (Figure 3). Although inflation pressure stabilizes, it does drop during the breaks in testing needed to measure fuel consumption. Inflation pressure will then have a slight increase during the next test run with final stabilization. Typically, during the warm-up run, inflation pressure increases by about 50 to 70 kPa above the cold inflation pressure. During the subsequent test runs, inflation pressure increases by 15 to 20 kPa (Table 2). These changes in inflation pressure during the test runs might have the potential to interfere with the SAE J1321 fuel consumption tests.

Relation between rolling resistance and inflation pressure in test tires

Regression coefficients from the SAE J1269 tests were used to estimate rolling resistance force of the tested tires over a range of inflation pressure (Table 3). A "Reference Pressure" was established as the cold inflation pressure used during the track tests (690 kPa (100 psi)

for drive and trailer, 760 kPa (110 psi) for steer). The reference test point consisted of the load on the tire during the track test, as listed in Table 2 and the Reference Pressure. Other test points were selected using the same loads as used for the reference test point and percentages of the Reference Pressure, referred to as “Relative Inflation Pressure.” The calculated rolling resistance values in Table 3 show a gradual decrease as the inflation pressure increases. The decreases in rolling resistance from the reference pressure (relative inflation pressure of 100%) to a relative inflation pressure of 110% (equivalent to a pressure increase of about 70 kPa) range from about 1% for the drive tires to about 1.3% for the steer tires, and about 2.5% for the trailer tires.

Because fuel consumption is related to the rolling resistance of the whole vehicle rather than the rolling resistance of the individual tire models mounted on each axle, the data in table 3 were converted to vehicle average rolling resistance coefficients by the following process:

- 1) Rolling resistance values were divided by the load and multiplied by 1,000 to obtain a rolling resistance coefficient (Cr) in kg/ton. This unit is most commonly used for comparing rolling resistance performance of different tire models and allows for evaluation of the rolling resistance independent of load.
- 2) A vehicle average rolling resistance coefficient was calculated for each of the three sets of tires using the measured axle load values of 18% steer, 41% drive and 41% trailer and the following equation:

$$Cr(vehicle) = (Cr(steer) \times 0.18) + (Cr(drive) \times 0.41) + (Cr(trailer) \times 0.41) \quad (2)$$

- 3) The values of the three sets of tires were then averaged and a standard deviation calculated.

The relation between relative inflation pressure and the vehicle average rolling resistance coefficient is plotted and shown in Figure 4. Note that although equation (1) suggests that the relation between rolling resistance and inflation pressure is hyperbolic, the difference between the hyperbolic and linear relations appears to be small enough that a linear approximation is adequate to describe the relation in the range of inflation pressures displayed.

Discussion

Rolling resistance coefficients were calculated for a wide range of relative inflation pressures using the linear regression approximation shown in Figure 4. These ranged from a relative inflation pressure of 50%, which is the criterion for a flat tire as determined by the Commercial Vehicle Safety Alliance [9], to one of 125%, which is somewhat higher than the highest inflation pressures recorded during the track tests. Table 4 shows the changes in rolling resistance coefficient relative to changes in inflation pressure as well as estimates of the change in fuel consumption associated with the change in inflation pressure. Changes in fuel consumption were estimated using the concept of the “Return Factor,” the ratio of the percent change in rolling resistance to the percent change in fuel consumption. A return factor of 5:1 is a common industry rule of thumb and was the value used by EPA to develop

the target values for verification of tires under the SmartWay program [3]. Return factors in actual use may vary somewhat; EPA measured one of 4:1 during recent road testing [3].

During the test runs, inflation pressure increased by 15 – 20 kPa, or an increase in relative inflation pressure from the reference of 100% to 102% to 106%. From table 4, a relative inflation pressure of 105% results in reductions in fuel consumption due to lower rolling resistance of 0.2% to 0.3%. Use of the regression equation in Figure 4 results in an estimate of reductions in fuel consumption of 0.09% to 0.16%. The SAE J1321 tests of aerodynamic components resulted in reductions in fuel consumption of 1.2% to 6.2%, with 95 percent confidence intervals of 0.9% to 1.1%. Thus the increase in inflation pressure during the SAE J1321 test runs had a very minor and barely measurable effect on the fuel consumption. On the basis of these results, it is unlikely that changes in inflation pressure during the test runs causes significant interference with the results of the tests.

The heating of the tires during warm-up and test runs also decreases hysteresis of the rubber in the tires, providing a source of decreased rolling resistance in addition to the decrease caused in increased inflation pressure. We do not have data available to determine whether the magnitude of the decreased hysteresis is enough to interfere with the SAE J1231 test results. However, although the air cavity temperatures do not appear to thermally stabilize during the test runs, the temperature changes during the test runs are considerably less than the temperature changes during the warm up. Thus, the effect of changes in elastomer hysteresis during the test runs is likely to be small.

There is a possibility that the systematic increase in ambient temperature during the test day (from about 25° to about 38° during all of the tests) could systematically lower rolling resistance during the test day, with the later test runs consistently having lower rolling resistance. In addition, systematic increase in ambient temperature of about 15° would also result in a systematic decrease in air density of about 2.5%, which would decrease aerodynamic drag and also reduce fuel consumption. The effect of these can be checked by looking at the raw fuel consumption during the SAE J1321 tests. Given that all other operating parameters are the same, a systematic decrease in rolling resistance should yield a systematic decrease in fuel consumption during the test day. The data do not show this to be the case. Out of the six test days examined in this analysis, only two days had a systematic decrease in fuel consumption. Although the increase in ambient temperature during the test day may, indeed, have some effect on rolling resistance and aerodynamic drag, this effect is probably not significant compared to other sources of variability in the test procedure.

The results shown here may also have implications regarding the magnitude of the relation between tire underinflation and fuel economy. However, understanding the nature of such implications will require SAE J1269 tests data from a wide range of tire models and SAE J1321 testing of trucks at varying degrees of tire underinflation.

Conclusions

On-board tire inflation and air cavity temperature monitoring demonstrates that the standard SAE J1321 fuel consumption test protocol does not fully stabilize tire temperature.

Furthermore, while inflation pressure does partially stabilize, inflation pressure during a test run can increase by 15-20 kPa. For the tires tested here, the relation between inflation pressure and rolling resistance coefficient can be approximated as being linear, with only modest decreases in rolling resistance and a corresponding decrease in fuel consumption of less than 0.2%. The estimated decrease in fuel consumption is dependent on the return factor selected, but there is not much difference between estimates made on the basis of a return factor of 5:1 and those made on the basis of a return factor of 4:1, two commonly used return factors. The estimated changes in fuel consumption are insignificant as compared to the observed variability of fuel consumption test results of 1% or greater. However, at very small reductions in fuel consumption, increased inflation pressure during a fuel consumption test might well affect the results, and those conducting such tests should account for it.

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FIG. 1 —.
Relation between air cavity temperature and inflation pressure for the steer tire, driver's side.

FIG. 2 —.

Time series plot showing changes in air cavity temperature during a typical SAE J1321 test, steer tire, driver's side.

FIG. 3 —.

Time series plot showing changes in tire inflation pressure during a typical SAE J1321 test, steer tire, driver's side.

FIG. 4. —.
Relation between vehicle average relative inflation pressure and vehicle average rolling resistance coefficient.

TABLE 1 —

Sample of tires and test conditions used for track and tire tests

Model	Axle Position	Frr ^a	Crr ^b	Cold inflation pressure for track test, kPa	Load during track test, N
Hankook AL 11	Steer	122	5.3	760	26289
Hankook AL 11	Steer	131	5.6	760	26289
Hankook AL 11	Steer	121	5.2	760	26289
Bridgestone M710 Ecopia	Drive	138	5.9	690	14848
Bridgestone M710 Ecopia	Drive	141	6.0	690	14848
Bridgestone M710 Ecopia	Drive	139	5.8	690	14848
Bridgestone R197 Ecopia	Trailer	109	4.7	690	15035
Bridgestone R197 Ecopia	Trailer	109	4.7	690	15035
Bridgestone R197 Ecopia	Trailer	108	4.6	690	15035

^aRolling resistance force, ISO 28580, 2m correction, in N^bRolling resistance coefficient, ISO28580, 2 m correction, in kg/ton, or N/kN

TABLE 2. —

Summary of inflation pressure changes during warmup and test runs

Date	Increase in inflation pressure during run, in kPa, mean of all tires on truck					Number of tires with valid data (out of 18 tires on truck)
	Warm-Up Run	Run 1	Run 2	Run 3	Run 4	
7/15/2015	71.7	17.9	15.9	13.1	--	Warm-up run: 10 All test runs: 18
7/16/2013	61.4	25.5	20.7	15.9	--	Warm-up run: 18 Run 1: 18 Run 2: 18 Run 3: 13
7/17/2013	63.4	24.8	17.9	15.2	17.2	Warm-up run: 18 Run 1: 18 Run 2: 13 Run 3: 14 Run 4: 13
7/18/2016	60.7	19.3	--	--	--	All runs: 18
7/20/2015	60.7	19.3	12.4	14.5	--	All runs 18
7/21/2016	57.2	15.2	17.2	15.9	--	Warm-up run: 18 Run 1: 11 Run 2: 10 Run 3: 9
7/23/2016	--	16.5	15.2	13.8	--	Warm-up run: data not collected Run 1: 18 Run 2: 15 Run 3: 14

TABLE 3—

Modeled rolling resistance force for various inflation pressures for test truck tires as calculated from J1269 regression coefficients.

	Reference inflation pressure							
Inflation pressure, steer, kPa	621	655	689	724	760	793	827	862
Inflation pressure, drive and trailer, kPa	552	586	621	655	690	724	758	793
Inflation pressure, % relative to reference for steer	82	86	91	95	100	105	109	114
Inflation pressure, % relative to reference for drive and trailer	80	85	90	95	100	105	110	115
Inflation pressure % relative to reference, vehicle weighted average	80	85	90	95	100	105	110	115
	Rolling resistance force, N							
Steer	145.6	144.2	143.0	141.9	140.9	140.0	139.2	138.4
	158.3	156.7	155.3	154.1	152.9	151.9	150.9	150.1
	147.3	145.8	144.5	143.3	142.2	141.2	140.3	139.5
Drive	99.8	99.0	98.2	97.6	97.0	96.5	96.0	95.5
	103.2	102.3	101.6	101.0	100.4	99.9	99.4	99.0
	98.5	97.6	96.8	96.1	95.4	94.8	94.3	93.8
Trailer	85.4	83.5	81.9	80.4	79.1	77.9	76.8	75.8
	81.9	80.4	79.1	77.9	76.8	75.8	74.9	74.0
	84.7	83.0	81.6	80.3	79.1	78.0	77.0	76.0

TABLE 4—

Percent change in rolling resistance and fuel consumption at various relative inflation pressures.

Relative inflation pressure	Crr ^a estimated from regression equation	Percent change in Crr ^a relative to reference value	Percent change in fuel consumption, RF ^b = 5:1	Percent change in Fuel consumption, RF ^b = 4:1
50	6.49	10.7%	2.1%	2.7%
60	6.37	8.6%	1.7%	2.1%
70	6.24	6.4%	1.3%	1.6%
80	6.12	4.3%	0.9%	1.1%
85	6.05	3.2%	0.6%	0.8%
90	5.99	2.1%	0.4%	0.5%
95	5.93	1.1%	0.2%	0.3%
100	5.86	0.0%	0.0%	0.0%
105	5.80	−1.1%	−0.2%	−0.3%
110	5.74	−2.1%	−0.4%	−0.5%
115	5.68	−3.2%	−0.6%	−0.8%
120	5.61	−4.3%	−0.9%	−1.1%
125	5.55	−5.4%	−1.1%	−1.3%

^aRolling resistance coefficient, in kg/ton^bReturn Factor, the ratio of the percent change in rolling resistance to the percent change in fuel consumption