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The Effect of Wheel Alignment on Rolling Resistance - A Literature Search and Analysis

by

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

Introduction

The purpose of this report is to examine the effect of front-end wheel alignment on rolling resistance. More specifically the effect of toe-in and toe-out are considered.

With the vital need to conserve the nations resources, there is an increasing demand for vehicle fuel economy. One factor that may considerably affect fuel consumption is tire rolling resistance. The rolling resistance is a function of many physical tire properties, such as rubber compound, tread design, inflation pressure, etc. With the exception of inflation pressure, most of these properties are fixed to the design of the tire. However, another factor that may vary during normal use of the tire, which has a significant effect on rolling resistance, is slip angle.

Slip angle may be defined as the angle between the plane of the tire and the forward direction of the vehicle. Slip angle is more commonly referred to as "Toe", which is measured as the difference in inches between the front centers and the back centers of the front wheels. (See Figure IA.) For most vehicles, 1/2 inch toe corresponds approximately to 1/2° slip angle. Toe-in refers to the tires directed inward toward the front-center of the vehicle. Conversely, toe-out refers to the tires directed outward from the vehicle (Figure IB). Since suspension effects cause the front wheels to toe outward as the vehicle moves forward, most vehicles have a manufacturer's recommended alignment setting at some toe-in condition. This is to ensure that the vehicle maintains a straight line during normal driving.

A misaligned wheel introduces an angle of slip which results in two forces which will affect fuel consumption: 1) a lateral force, (Fy), which is normal to the plane of the tire. 2) a longitudinal force (Fx), which lies in the plane of the tire (see figure IC)). The components of these two forces, in the direction opposite to the direction of forward motion, are summed to give the effective rolling resistance (F_R) at the given slip angle (α). Mathematically, this rolling resistance can be expressed as:

$$F_R = Fy \text{ SIN } \alpha + Fx \text{ COS } \alpha \qquad 1$$

It is the change in the effective rolling resistance at slip angle (α), as compared to the base rolling resistance at zero slip angle, which causes the overall effect on fuel consumption.

This report analyzes the effect of toe-in and toe-out on rolling resistance, based on the road load results of an EPA test program. Secondly, it correlates these results with the results of slip angle vs. rolling resistance data, found in the existing literature. Then a survey of vehicle safety inspections is used to approximate the number of vehicles in a misaligned state, and finally an estimate of the effect on fuel economy is discussed.

Discussion

A. EPA Test Program - Design/Results

A test program was conducted in late October (1977), using a 1971 Vega station wagon, at the Transportation Research Center of Ohio, to determine the effect of front-suspension alignment on vehicle road load (1). The driveshaft torque was measured, on a flat roadway, at approximately 50 mph for three different alignment states: (1) manufacturer's recommended setting (1/4" toe-in), (2) 1/2" greater than the maximum recommended setting (7/8" toe-in), (3) 1/2" less than the minimum recommended setting (3/8" toe-out). A minimum of three tests was conducted in each direction for four different sets of tires: steel belted radials, bias ply, bias belted, and fiberglass belted radial tires. (The fiberglass belted set was not tested at the toe-out condition.) Each set of tires was warmed up for 30 minutes at steady state 50 mph prior to testing.

For the 3/8" toe-out condition, the three sets of tires tested all showed a significant increase in driveshaft torque as compared to the baseline 1/4" recommended toe-in. The increase was approximately 30% for the radial tire, while bias and bias belted tires showed increases of 75% and 22%, respectively (see Table 1).

Similarly, for the 7/8" maximum toe-in condition, with both the fiberglass and steel belted radials, driveshaft torque increased about 23% as compared to the baseline. However, a slight decrease was detected at the same condition for the bias ply and bias belted tires.

B. Literature Search

The significance of these results, along with the discrepancy that occurred with the bias tires, warranted further investigation into this area. However, due to the development of equipment problems and the unavailability of another vehicle equipped with a driveshaft torquemeter, a limited data base was obtained. Therefore, a search of the literature for supporting data was conducted. Although no evidence of any road tests involving vehicles with various alignment conditions has been found, there were some available data on the effect of slip angle on rolling resistance. In order to compare these data with the results of toe-out and toe-in conditions on the Vega, it was assumed that the change in driveshaft torque was mainly related to the change in effective rolling resistance due to the angle of slip. However, the front suspension properties should also contribute to the overall effect. All the slip angle vs. rolling resistance data that have been acquired were measured with either a flat bed machine or a large roll dynamometer on tires not connected to a vehicle front-end suspension system. Furthermore, the test conditions were different for each of the four available sources of slip angle data.

Test results published by W.W. Curtiss for a steel belted radial tire showed about a 25% increase in rolling resistance for a 1° change in slip angle (2). (See Figure IIA.) These tests were conducted on a large roll dynamometer at various speeds up to 60 mph.

Similar test results, presented by Walter and Conant of Firestone Tire Co. (3) for a bias ply tire also showed about a 25% increase in rolling resistance for a 1° increase in slip angle (see Figure IIB). These tests were conducted at 30 mph on a large roll dynamometer.

A much smaller effect was detected by tests conducted at Calspan Corporation (4). Three tires were tested (bias ply, bias belted, radial ply) on a flat bed machine at 50 mph. Rolling resistance increased for an increase in positive slip angle as well as negative slip angle for both bias tires (see Figure III). At 2° slip angle in either direction the increases in rolling resistance ranged from 3% to 9%. However, a decrease of approximately 25% was observed at +2.5° slip angle in the radial ply tire, and a decrease of about 15% was seen at -1.5° slip angle. Rolling resistance reached two distinct minima at these points, after which it increased with increasing magnitudes of slip angle. Similar tests were conducted at Calspan on three different truck tires for both positive and negative slip angles (5). The results showed a very symmetric curve about 0.0° slip angle with a parabolic shape of increasing rolling resistance with increasing magnitude of slip angle (see Figure IV). Approximately a 40% increase in rolling resistance was observed at 1° slip angle, while at 2° slip angle the increase was almost 100%. The results were nearly identical for each of the three different tires tested.

C. In-Use Condition

In order to estimate the number of in-use vehicles that are misaligned to an extent which will have some effect on fuel economy, a survey of state and city vehicle safety inspections was conducted. However, only four of the twenty-two states contacted include a front-end alignment check. Of these four, only two have responded with data.

Both the State of New Jersey and Cincinnati, Ohio reported approximately 7% of the vehicles inspected annually, failed inspection due to wheel alignment (6). In all cases, these vehicles were tested on scuff gages, with failure criterions of 40 - 50 ft/mile or approximately 0.5° slip angle. (A scuff guage measures the number of feet of side scuff per mile of forward motion.) However, this equipment is not very accurate and tends to underestimate the degree of misalignment. Also, those few states that do conduct wheel alignment inspections are expected to have a lower percentage of misaligned vehicles than those that do not.

Another, perhaps more accurate investigation, was conducted by the U.S. Department of Transportation which included a front end alignment inspection of 125,000 vehicles in five states (7). (Alabama, Tennessee, Arizona, Pureto Rico, and Washington, D.C.) The vehicles were inspected for toe-in, toe-out, caster, and camber on Hunter alignment guages. The criterion for failure was the manufacturer recommended maximum settings which may range from 1/16" to 1/2". The rate of failure was approximately 19%.

D. Estimated Effect on Fuel Economy

In order to estimate the effect of front-end misalignment on fuel economy, the worst and best cases were considered.

The greatest effect (worst case) is observed from the actual road test data in which driveshaft torque was measured. A criterion that a 10% change in road load yields approximately a 3% change in combined fuel consumption, was used (8). The change in driveshaft torque for all 7 conditions, presented in Table 1, was averaged to obtain a mean increase in driveshaft torque of 23% over the aligned condition. This corresponds approximately to a 7% decrease in fuel economy.

A less severe effect on fuel consumption is obtained when only the effect of slip angle on rolling resistance is considered. From the literature data, approximately a 25% increase in rolling resistance was observed for a 2° change in slip angle.

It has been observed at EPA that a 10% change in rolling resistance will yield approximately a 1% to 2% change in fuel consumption (9). This slip angle effect might be considered as a best case for the effect of wheel alignment on fuel economy. The average vehicle with a front-end misalignment is expected to lie somewhere between these best and worse cases, that is, a 3% to 6% decrease in fuel economy is estimated for the average misaligned vehicle.

Conclusions

Overall, a large number of in-use vehicles operate with a front suspension system in a significantly misaligned state. Although the major incentive to correct such a condition would be to prevent increased tire tread wear, an additional incentive may be to improve the overall fuel efficiency of the vehicle. The fuel economy benefit, in some worse cases, may be in excess of 7% based on the road tested vehicles. However, data indicates that for some front-end systems with certain tires, the optimum state with respect to both tire wear and fuel economy may be at some misaligned condition. Both the EPA road tests and the slip angle vs. rolling resistance data indicate that the latter is the exception to the rule. Therefore, in general, one may conclude that improper wheel alignment will tend to decrease the fuel efficiency of most motor vehicles. The magnitude of this effect is most appropriately obtained from the actual road tests. It is estimated that approximately 10% of the motor vehicles in-use, operate with about a 4% decrease in fuel efficiency, due to improper front-end wheel alignment. With more than 105 million registered passenger motor vehicles in the U.S., that travel almost 1 trillion miles annually(10), an overall annual savings of over 5 million barrels of gasoline (approximately 0.3 billion dollars) may be gained by nation-wide proper wheel alignment.

Recommendations

Based on this study, the effect of front-end wheel alignment on fuel economy can be considered quite significant. Not only does this phenomenon affect the overall energy efficiency of the nations in-use vehicle fleet, but it may also be an important factor in motor vehicle test programs. In fact, the possibility to under load a vehicle at a misaligned condition, as compared to the recommended alignment setting, exists. Therefore, further testing in this area is recommended. The most appropriate tests would be actual road tests, such as the previous EPA test program, with several vehicles and tires, representative of the current market. Alternatively, slip angle vs. rolling resistance testing, on an appropriate tire test machine, may be sufficient to predict the effects of wheel alignment, given the physical characteristics of the tire. Furthermore, a public awareness compaign is suggested in order to inform the motor vehicle owners of this information.

Forward Direction

(Top View)

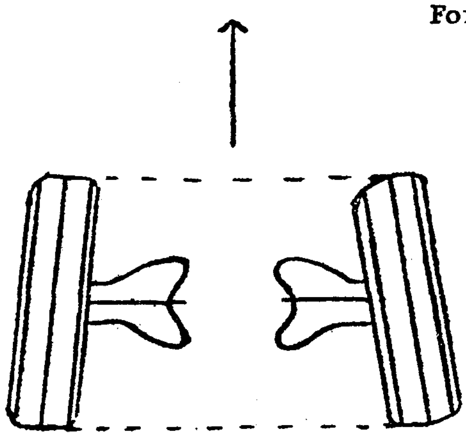


Figure IA. Toe-In

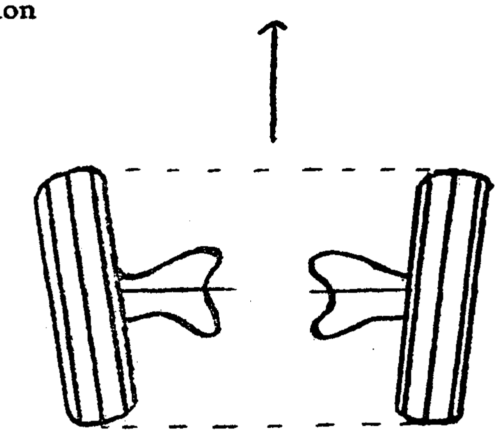
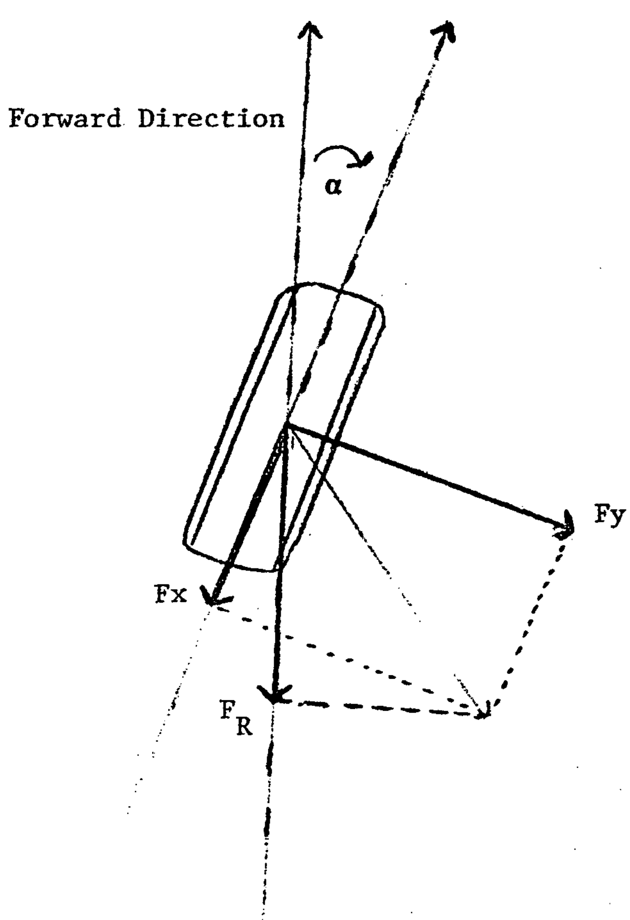


Figure IB. Toe-Out



α = Slip Angle
Fx = Longtudinal Force
Fy = Lateral Force
F_R = Rolling Resistance

Figure IC.

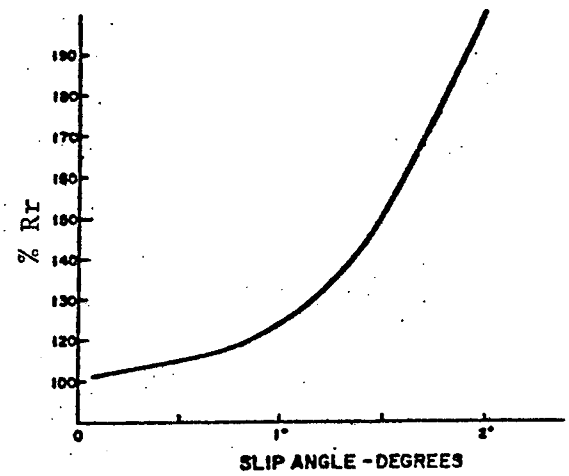
Table 1

Mean Torque for Each Tire/Alignment State Combination

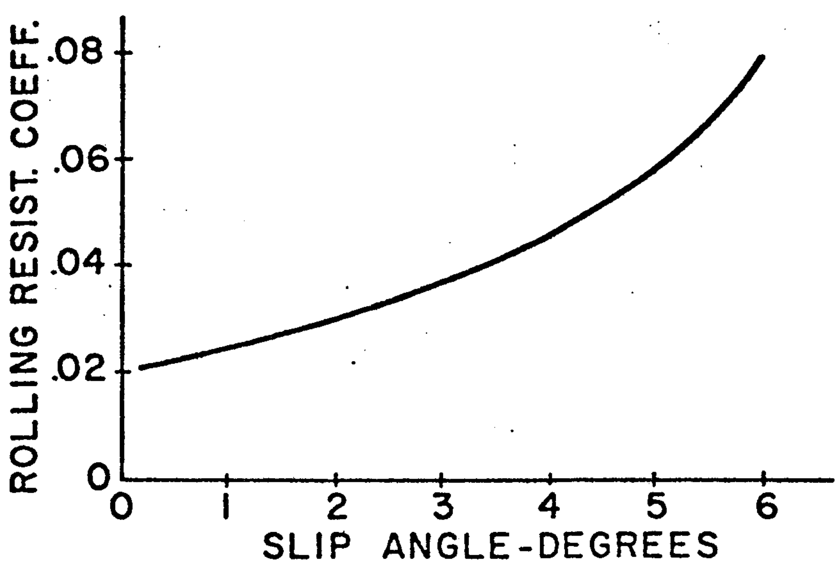
Tire Type	Mean Torque(ft-lbs)	Coefficient of Variability ($\sigma/\bar{x}Z$)	Alignment Setting (Toe-In (inches))	
Radial (1)*	41.535	3.087	0.250	Baseline
Bias Belted	41.218	1.877	0.250	
Bias	42.406	2.995	0.250	
Radial (2)**	38.520	1.212	0.250	
Radial (1)*	47.788	2.002	0.875	1/2" greater than mfr. recommended max. setting
Bias Belted	38.728	4.701	0.875	
Bias	37.908	4.657	0.875	
Radial (2)**	47.476	2.037	0.875	
Bias Belted	50.193	3.648	-0.375	1/2" less than mfr. recommended min. setting (toe-out)
Bias	73.996	2.056	-0.375	
Radial (2)**	53.750	3.158	-0.375	

* Fiberglass Belted
** Steel Belted

Figure II

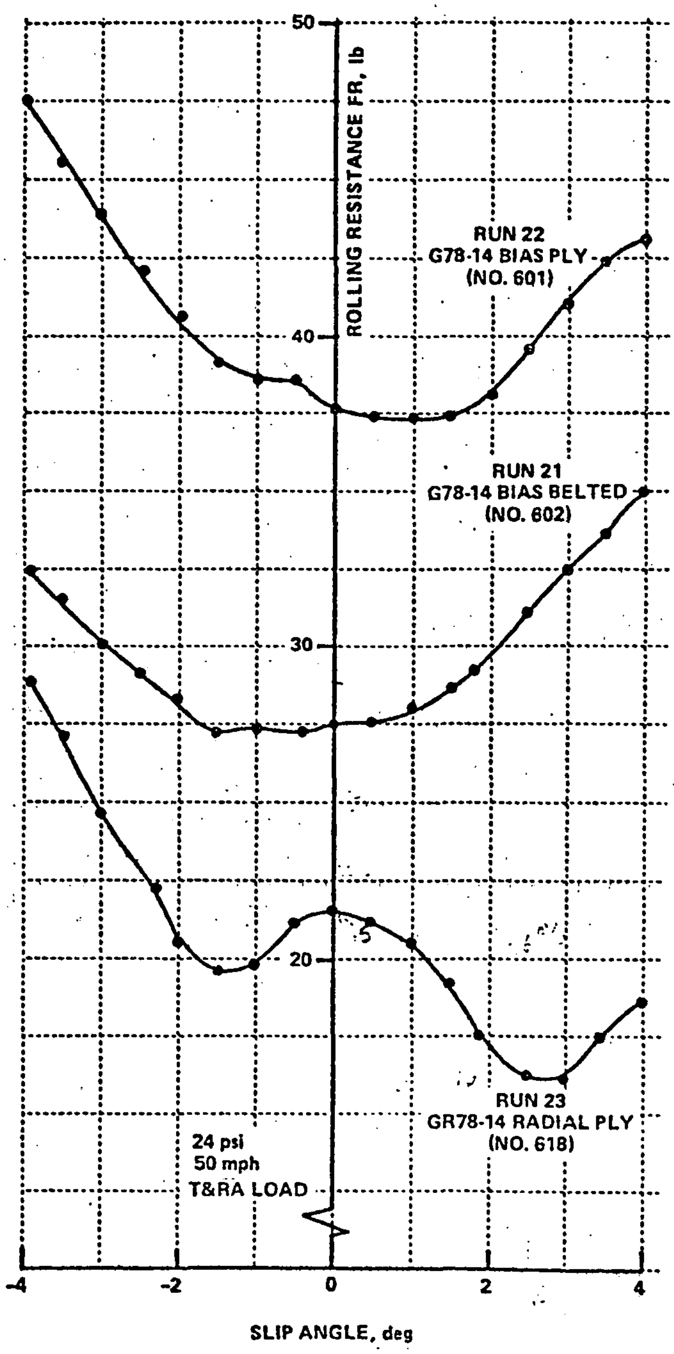


A. Percent Increase in Rolling Resistance (Rr) vs. Slip Angle (2). (100% Rr corresponds to Rolling Resistance at Zero Slip.)



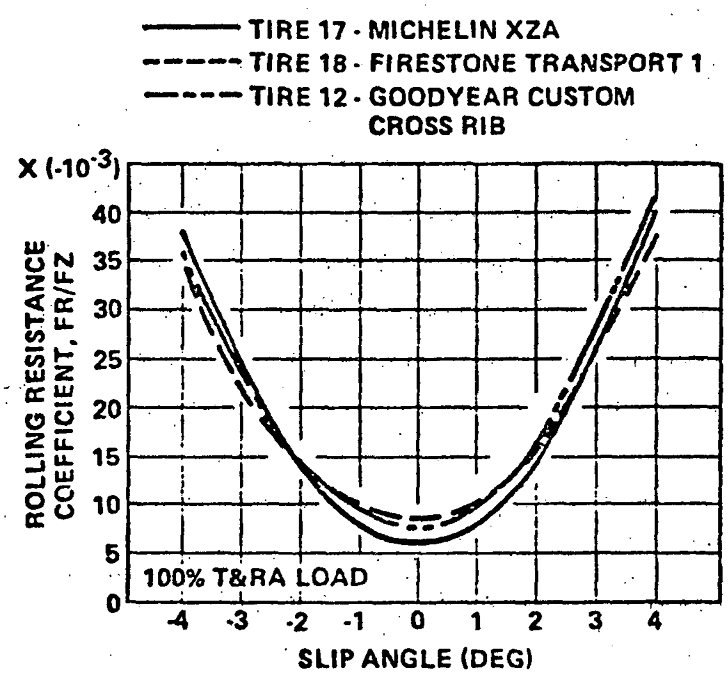
B. Rolling Resistance Coefficient vs. Slip Angle (3).

Figure III



ROLLING RESISTANCE VS SLIP ANGLE (AT CONSTANT TEMPERATURE) ON FLAT ROADWAY (4).

Figure IV



Rolling Resistance Coefficient
vs. Slip Angle for Truck Tires (5).

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