Development of a Mobile Tire Test Dynamometer and Tests of Three Truck Tires

W. Mercer¹ W. Stephenson¹

ABSTRACT

The Ontario Ministry of Transportation and Communications (MTC) carried out a commercial vehicle accident survey which found that loss of tire traction was an important factor in a majority of loss-of-control accidents. In particular, the survey showed that the centre-rib bias-type traction tire was significantly overrepresented in loss-ofcontrol accidents.

Since little information was available relating to commercial vehicle lateral tire traction under the conditions in which these accidents occurred, MTC designed and built a mobile dynamometer capable of measuring the instantaneous forces at the tire/pavement interface. Provision was made for adjusting the vertical load, steer angle, and water depth, thus simulating wet road driving conditions at the test wheel.

Tests were conducted to measure the sideforce and braking characteristics of the centre-rib, biastype tire in comparison with radial ply, mud-andsnow-type and bias ply, rib-type traction tires.

It was concluded that the characteristics of the centre-rib tire were consistent with the findings of the accident survey.

1. INTRODUCTION

A vehicle's ability to manoeuvre is directly linked to the capability of its tires to transmit force to the road surface. The transmission of force is greatly influenced by the inherent tread depth, properties of the tire, inflation pressure, and the nature of the roadway surface. If a manoeuvre demands more force than the tires can transmit, adhesion to the road is lost and loss of control of the vehicle may result.

An MTC survey of commercial vehicle accidents (1) investigated a number of serious accidents in great

depth. The survey included details such as tire type, inflation pressure, and tread depth. It found that the centre-rib tread-type tire was statistically overrepresented on drive axles of vehicles involved in loss-of-control accidents. It also found that tire inflation pressures were typically at or above the manufacturer's recommended value for maximum load, even though the vehicle was operating empty or lightly loaded.

Literature surveys (2,3,4) revealed that tires are prone to lose sideforce and tractive capability with tread loss and footprint alteration. The footprint alteration is caused primarily by varying inflation pressure and/or vertical load.

In particular, tires used on the drive axle of a tractor-trailer combination reflect the jackknife sensitivity of the vehicle. Jackknifing is imminent when the rear tire set of the tractor loses its sideforce capability and, hence, provides little or no resistance to lateral motion. Compressive forces within the truck tend to induce a "buckling" at the articulation joint. This buckling phenomenon is reacted at the tractor's rear tires, and the ensuing displacement is proportional to the sideforce available at those tires.

As a result of the above surveys, it was decided that there was a need to investigate, in detail, the longitudinal and lateral traction characteristics of truck tires in a "real life" environment. Toward this end MTC undertook the development of a mobile tire test dynamometer.

2. MOBILE TIRE TEST DYNAMOMETER

Design requirements for the tire test dynamometer stipulated that it must have the capability of simulating wet road, lightly laden tires operating at controlled side-slip angles and the normal speed limit on public highways. With these requirements as guidelines, MTC chose a standard, tandem-

Automotive Technology and Systems Office, Transportation Technology and Energy Branch, Ontario Ministry of Transportation and Communications, Downsview

axle, 13.7 m (45 ft) flat bed as the basic unit on which the test apparatus would be constructed.

A unique 3-axis truck wheel force transducer (5. 6) similar to one built for the Federal Highway Administration but with increased sideforce sensitivity (7) and improved rust-corrosion resistance was procured. This unit mounted directly to a standard 10-stud, 28.6 cm (11 1/4 in) bolt circle. disc wheel hub. Demountable rims and tires. single or dual, such as those used on spoke-type wheels, mounted to the outer surface of the unit. Figure 1 shows this device as mounted on the vehicle. It consists of two concentric steel tubes attached by a flat plate at the outer end (Figure 2). The inner tube attaches to the disc wheel hub while the outer tube provides the mount for the rims and tires. Strain gauges were located on the inner surface of the inner tube and oriented such that bending and torsional forces cancelled. Electronic circuitry for amplifying the strain gauge signals and a wheel rotational position sensor were located within the transducer. Signals were output from the hub through a slipping assembly and routed to additional electronics for separation of the vertical, horizontal, and lateral force components.

The test trailer had an air lift drop axle mounted midway between the kingpin and rear tandem axle set (Figure 3). The force transducer was mounted on the left end of this special test axle. Vertical load on the test axle was controlled by means of a sensitive pressure controller and the air bag suspension system. A local digital read out from the force transducer was located adjacent to the pressure controller, permitting accurate setting of the desired vertical load. Steer angle of the test tire was provided by double acting hydraulic cylinders and a counter steering system (8) which produced a toe-in, toe-out capability. This approach was taken to prevent yawing of the trailer during testing, thereby eliminating erroneous steer angles. Flow control valves were incorporated to facilitate adjustment of steer scan rates if automatic scan was selected, or fine control of steer angle when fixed steer was used.

Water for wetting the road in front of the tires on the test axle was carried on board the trailer in four 1100 L (250 gal) pressure vessels. Air pressure from a trailer mounted, engine driven compressor was applied to the tanks and air cylinders to raise the water spray nozzles located forward of the test wheel. During testing, the pressurized water was released through electrically controlled, air-operated valves to a manifold, a flow control gate valve, and a turbine flow meter. To maintain a constant water depth on the road, the flow, control valve was calibrated in terms of forward velocity and the turbine flow meter output was displayed to the operator in km/h. Typically, with a water swath 61 cm wide (2 ft) by 0.9 mm deep



Three-axis wheel force transducer as mounted on the test vehicle FIGURE 1

Section through tire force transducer, wheel and tire FIGURE 2

(approximately 1/32 in) and a velocity of 80 km/h, a flow of 13.6 L/s (3.0 gal/s) was required. Water flow to the non-test wheel was controlled but not monitored. Small variations in water flow were found to have no significant effect on the test results. Total test time available from the supply tanks was 165 s at 80 km/h. During the initial tests, speed was restricted to 60 km/h or 220 s total duration. This capacity made it possible to conduct 10 test runs or approximately one hour of operation before replenishing the water supply.

An electrical control box permitted pre-selection of certain test conditions such as braking, steering, brake and steer together, manual steer from the tractor, or automatic steer scan. Safety interlocks were provided such that steering or braking were not permitted until the axle was commanded down and water flow had been initiated.

A remote control box located in the tractor permitted the operator to continuously monitor steer angle, longitudinal, lateral, and vertical forces on the test wheel, and the water flow. Once the electrical control box was programmed for testing, the whole sequence was initiated either by a photo cell under the tractor which sensed the test start point or manually by a single switch on the remote control. Termination of a test, for any reason, required only a single switch to be turned off, which immediately raised the axle, released the brakes, and stopped the water flow.

Data from the test vehicle was electrically conditioned, FM multiplexed, and transmitted from the test tractor on a radio frequency telemetry link. At a base station the incoming data was received,



Tire sideforce test vehicle FIGURE 3

de-multiplexed and fed to a Hewlett-Packard 1000 A700 computer. The computer manipulated data was analyzed in detail (9), a summary of which is contained in the following sections.

3. TEST METHODOLOGY

Three different types of traction tires were selected for testing, identified as tires A, B, and C. Details relating to general construction and load ratings were as follows, with tread patterns as shown in Figure 4.



Tire B



Tire under examination FIGURE 4

- Tire A 10:00-20 F bias ply tube-type tire of center-rib tread design, with a maximum load rating of 2468 kg (5430 lb) at 586 kPa (85psi) cold for a single tire and 2164 kg (4760 lb) at 516 kPa (75 psi) cold for dual tires. Tread depth new was 22.5 mm (28/32 in).
- Tire B 11R 22.5 radial ply mud-and-snow-type tire, with a maximum load rating of 3005 kg (6610 lb) single and 2705 kg (5950 lb) dual at 793 kPa (115 psi) cold. Tread depth new was 17.5 mm (22/32 in).
- Tire C 10:00-20 F bias ply rib-type tire, with a maximum load rating of 2468 kg (5430 lb) at 586 kPa (85 psi) cold for a single tire and 2164 kg (4760 lb) at 516 kPa (75 psi) cold. Tread depth new was 14.5 mm (18/32 in).

All of the selected tires were standard-use, commercially available and purchased from local tire dealers. All were subjected to the same tests and treated in an identical manner.

The test program was designed to measure the lateral and longitudinal forces generated at the road surface as a function of inflation pressure, vertical load, slip angle, and tread depth. Other factors which influence the force capability of a free rolling tire are:

- camber angle
- roadway surface texture
- tread pattern
- tire texture
- foreign matter/moisture in contact patch
- roadway and tire temperature
- tire material
- ply orientation

To evaluate the three test tires, it was necessary to control most of these variables. A consistent vertical load/slip angle application scheme was used. Water was discharged onto the road surface in a constant pattern and at a rate calculated to give a depth of 0.9 mm. The test track area was monitored to detect changes due to temperature and texture. The test wheel camber angle was maintained near zero at all steer angles and all tires were shaved and buffed to a smooth surface and uniform contour. A test speed of 60 km/h (36 mph) was used for all tires.

Two distinct types of tests were conducted:

Test Matrix: Tire/Tread/Pressure/Combinations

Tire	Tread depths					Inflation presure				
A Centre-Rib Bias 10:00-20 F	(mm) (in)	22.5 28/32	16 20/32	7 9/32	1.6 2/32	(psi)	(kPa) 70	483 586 85 (rec.)	110	759
B Radial M&S 11R M&S 22.5	(mm)	17.5 22/32	12.5 16/32	8.0 10/32	1.6 2/32	(kPa)	690 100	798 115 (rec.)	965 140	
C Bias Rib	(mm)	14.5 18/32	10.5 13/32	6.5 8/32	2.5 3/32	(kPa)	483 70	586 85 (rec.)	759 110	
Sideforce test		40.000		40-000-00						
Tire	Tread depth	Pressure		Vert. load			Steer angle			
All	All	Aİ		0-2500 kg (0-5560 lb)			2*, 4*, 6*, 8*			
Brake test										
Tire	Tread depth	Pressure		Vert. load			Steer angle			
All	All	All	All		1590 kg (3500 lb)		0*			

- free rolling with preset slip angles to examine lateral forces;
- braking with zero slip angle to examine longitudinal forces.

It was considered beyond the scope of this test program to combine braking with preset slip angles or braking while steering although the vehicle was capable of generating this data.

The test requirements called for the force characteristics of the three different tire types to be compared at four tread depths:

- full tread as manufactured with 800 km (500 mi) run-in;
- a tread depth representing two-thirds of each tire's usable tread, buffed to a smooth finish;
- a minimum legal tread, buffed to a smooth finish.

Further, each of the tires was tested at three inflation pressures:

- manufacturer's recommended pressure for maximum load;
- recommended, less 103.5 kPa (15 psi);
- recommended, plus 172.5 kPa (25 psi).

Four tires of each type were used and cross-checked at the end of a series of test runs to verify and validate, where necessary, performance uniformity within the sample. At regular intervals in the test program, a calibration tire was mounted and tested to determine any changes in the surface of the course during the test phase.

4. RESULTS AND DISCUSSION

4.1 EFFECT OF INFLATION PRESSURE ON SIDEFORCE

Figure 5 shows the percentage loss of sideforce for the three tire types between the new and fully worn states. The percentage loss is shown for three inflation pressures and two vertical loads, as a function of slip angle. The percentage loss of sideforce coefficient is the difference between the sideforce coefficient of a fully worn tire and that of a new tire and is expressed as a percentage of the new tire value for the same test conditions.

Tire A exhibited the greatest loss of sideforce over the slip angles investigated. This loss was evident at low slip angles and then was relatively uniform across the slip angle range. Tire C, another bias ply tire, showed a similar but less extreme results.

At the lower load of 909 kg (2000 lb), the sideforce difference between high, low, and recommended air pressure was more pronounced than at the higher load of 2273 kg (5000 lb).

Tire B showed a progressive loss as slip angle was increased. Similar to tire C, it showed little sideforce loss as a result of inflation pressure at the higher loads.

At higher loads, sideforce losses as a result of inflation pressure seemed minor, between 10 and 20%, and in the case of tire A, no change was noted.

Figure 6 shows the percentage change in sideforce coefficient for the three tires as a function of slip angle, for high and low inflation pressures, and with new and worn tread. The reference sideforce coefficient for Figure 6 is the tire noted at recommended inflation pressure.

Figure 6a and 6c compare the three tires in new and worn states at high inflation pressure, with low vertical load. They exhibit rather large losses in sideforce coefficient. As shown in Figure 6a, all new tires displayed a significant loss at 2 slip but then recovered at larger slip angles. The worn tires at high pressure (Figure 6c) lost sideforce coefficient at all slip angles, with tire A losing 60% at 7, much more than the other two. The losses were small at a load of 2273 kg (5000 lb) (Figures 6b and 6d). The worn tires at low pressure and low load exhibited an increase across the slip angles examined, with increases as high as 50% for tires A and C, as shown in Figure 6g.

Figure 7 summarizes the recorded data and shows the differences in sideforce coefficient as a result of inflation pressure. The most dramatic loss was for tire A at high inflation pressure, fully worn at low load. The sideforce coefficient plot began low and remained low across all slip angles investigated. Tire B, fully worn, exhibited the same low sideforce coefficient but only at high slip angles. Slip angles of 5 to 8 exhibited relatively high sideforce. Tire C showed trends similar to those of tire B, with slightly higher sideforce coefficients.

4.2. EFFECT OF TREAD DEPTH ON SIDEFORCE

It is evident from Figures 8 and 9 that tire A showed the largest losses in sideforce at all slip angles. As the summary in Figure 10 shows, tire A exhibited the greatest percentage loss from two-thirds working tread to minimum tread. Tire B tended to exhibit an initial increase in performance and Tire C, although not a stud-type tire, showed a similar tendency.

All tires experienced decreasing losses in sideforce coefficient as the vertical load was increased. In almost all cases, the highest absolute loss in sideforce coefficient occurred at 8 slip, with tire A at low load showing significantly higher losses than the others. Maximum sideforce coefficient decreased with load decrease, as did the slip angle at which it occurred.

The families of sideforce coefficient vs. tread depth curves (Figures 8, 9) reveal that a particular tire's

H = HIGH PRESSURE

R = RECOMMENDED PRESSURE



Percentage loss of sideforce coefficients of fully worn tires at different inflation pressures, using new tire as reference FIGURE 5



Percentage increase in sideforce coefficient at different slip angles for low and high inflation pressures, new and worn tires, using recommended pressure at given load and slip angle as reference

FIGURE 6





sideforce trends were similar throughout its slip angle history: however, the trend of each tire was distinct from the others. In general, tire A's curve tends to concave upwards, whereas tire B's curve does the opposite. The curve of tire C lies between those of tires A and B.

The area under the average sideforce coefficient vs. slip angle curve at a given vertical load is a comparative indication of overall tire performance at that particular load. Although it does not measure the tires quantitatively, it does add qualitative dimension to the overall performance spectrum. A relatively large area under the curve generally indicates a tire that performs well over its slip angle regime. However, care should, be taken when viewing such data because of the inconsistent nature of certain curves. The curves examined



Percentage available sideforce coefficient at $\alpha = 2, 4, \text{ and } 6^{\circ}, F_2 = 2000 \text{ lb. (909 kg) based}$ on new tire at given load and slip angle FIGURE 8

here yielded relatively uniform characteristics; therefore, the area under each curve can be taken as a rough measure of overall performance.

As can be seen from Figure 11a, for a new tire and a vertical load of 909 kg (2000 lb). The curve of tire A yields the highest area. As tread depth was reduced, tire A area quickly fell below that of tires B and C. Figure 11b shows a similar trend for a vertical load of 2273 kg (5000 lb).

Figure 12 superimposes the data from Figure 11 and is representative of an overall performance envelope summary. It is readily apparent that tire A was characteristically different from B or C and tended to lose curve area at a more rapid rate than the other two.



Percentage available sideforce coefficient at $\alpha = 2, 4, \text{ and } 6^{\circ}, F_z = 5000 \text{ lb.} (2273 \text{ kg}) \text{ based}$ on new tire at given load and slip angle FIGURE 9



Total sideforce loss envelope between 909 to 2273 kg Fz and 2 to 8' lateral slip (based on new tire as reference) FIGURE 10



Area under average sideforce coefficient vs. sideslip curves (plotted against tread depths at two vertical loads) FIGURE 11

4.3 EFFECT OF INFLATION PRESSURE ON BRAKING

The longitudinal peak and slide (brake coefficients) were measured and recorded. As with previous data, the area under the brake coefficient vs. tread depth curve was measured and is shown in Figure 13. The basis for comparison was tire B at recommended pressure. As can be seen, the effect of altering inflation pressure did not yield results consistent or dramatic. The overall braking performances of tires A and C were similar, whereas B showed a higher peak. The slide was similar for all three tires.

A close examination of the data indicated that at the high inflation pressure all tires experienced the largest percentage loss in longitudinal.

4.4 EFFECT OF TREAD DEPTH ON BRAKING

The slide and peak values were plotted against tread depth for recommended pressure (Figure 14). At the minimum tread depth, tire A had a μ slightly less than the other two. At new tire conditions, tire A was better than the other two. As the



Performance envelope (showing area under average sideforce coefficient vs. sideslip curve at low (909 kg) and high (2273 kg) Fz at different tread depths) FIGURE 12

tires wear, the values of peak and slide drop off accordingly, although the initial slope of the tire A curve is more pronounced than the other two.



Braking performance (as shown by area under μ vs. tread depth curves using tire B at recommended pressure as reference tire) FIGURE 13



 μ peak and μ slide at various tread depths for tires A, B and C at recommended pressure FIGURE 14

4.5 WORST CASE CONDITIONS

An examination of the sideforce data revealed that the greatest sideforce coefficient loss occurred in tire A. The conditions were bounded by a new tire at recommended pressure and a fully worn tire at high pressure, both at a load of 909 kg (2000 lb). The comparison can be seen in Figure 15. Figure 15a shows the actual sideforce coefficient spread and Figure 15b shows the percentage loss for all three test tires. Tire B tended toward a similar maximum percentage loss, but as can be seen from Figure 15b, its loss was progressive over the whole sideslip range. Tire A tended to lose approximately 75% initially at 1 and then at a shallow rate up to 91% loss at 8. Thre C's loss curve was similar, but less dramatic, than that of tire A. The initial loss was approximately 55%, with a maximum of 68%.

A worst case condition was not as pronounced nor consistent with braking, possibly due to the fluc-



Sideforce coefficient and percentage sideforce coefficient loss (based on new tire) plotted against sideslip angle for worst case condition FIGURE 15 tuating effect that inflation pressure had on a braking tire.

5. CONCLUSIONS

Higher inflation pressures tended to cause greater losses in sideforce at low, vertical loads. Inflation pressure had little effect on sideforce at higher vertical loads. Tire A appeared more sensitive to pressure change at higher slip angles, whereas tires B and C showed a lower sensitivity at lower slip angles. Further, tire A showed the largest percentage sideforce loss due to inflation pressure.

Worn tires at low pressure and low vertical load had better sideforce characteristics than at recommended or high pressures. All tires showed a marked loss in sideforce in their worn state at high pressure, compared to recommended pressure. Specifically, by increasing the air pressure of tire A from 85 to 110 psi (586 to 759 kPa) at low load, sideforce dropped between 30 to 60%. Tires B and C lost approximately 20%.

All tires lost sideforce capability between the new and fully worn test conditions. Tire A sideforce loss coincided with the onset of tread loss. Tire B, the radial stud tire, actually showed an improvement over new conditions at two-thirds working depth but then lost capability as more tread was worn away. Tire C lost sideforce capability rather proportionally to tread loss. All tires lost the largest percentage of sideforce coefficient at the largest slip angles tested. As tread depth was decreased, the slip angle at which sideforce coefficient was greatest for a given load decreased. This indicated a deterioration of overall tire performance.

In a worst case situation, comparing all three tires under extremes of performance, tire A lost 91% of its overall sideforce capability at high slip angles, compared to 85% for tire B and 68% for tire C. This loss was more immediate with tire A. In the cases examined here, the worst condition was experienced at low tread depth, virtually a "bald" (2.4 mm tread depth) tire at high inflation pressure (recommended pressure +25 psi (172 kPa), and low load.

During braking, it was found that tire A had the largest initial peak and slide values, well above those of tires B and C. However, it had lower peak and slide values than the other two tires at the lowest tread depth. In general, tire A had initial sideforce and braking properties equal to or better than tires B and C. However, tire A tended to lose its capability at a faster rate than the other two. In the extreme situation, comparing a new tire at recommended pressure to a fully worn tire at high pressure, both at low vertical load, tire A demonstrated a high magnitude loss across the slip angle range of the tire, culminating at a 91% loss at 8 slip.

6. REFERENCES

- Wolkowicz, M.E., and Billing A.M., "Commercial Vehicle Accident Survey," Ontario Ministry of Transportation and Communications, Research Report RR 235, January 1982.
- Dijks, A., "Wet Skid Resistance of Car and Truck Tires," Tire Science and Technology, Volume 2, No. 2, May 1974, pp. 102-116.
- Williams, T., and Meades, J.K. "Effect of Tread Pattern Depth and Tire Grooving on Lorry Tire Skidding Resistance," Transport and Road Research Laboratory, Crowthorne, U.K., Laboratory Report 687, 1975.
- Sabey, Barbara E., Williams, T., and Lupton, G.N., "Factors Affecting the Friction of Tires on Wet Roads," SAE Paper 700376, 1970.
- Wheel Force Transducer "OPERATION MANUAL" Maritime Dynamics Inc., MD-OM-1191-01, March 1982.
- Lysdale C.A., and Hegmon R.R., "Development of a Truck Wheel Force Transducer," SAE Paper 800247, February 1980.
- Truck Wheel Force Transducer "Specification," Ontario Ministry of Transportation and Communications, Specification No. MTC-CVOS-81-01/1, 1981.
- Shostak, B.E., "Truck Tire Traction Tester," University of Waterloo, Faculty of Mechanical Engineering, Student Report 80123396, January 1982.
- Mercer, W., "Comparison of Lateral and Longitudinal Traction Characteristics of Three Heavy Truck Tires," Ontario Ministry of Transportation and Communications, Report No. CV-85-02, December 1985.