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Tire Friction During Locked Wheel Braking

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ABSTRACT

Accurate values of tire-roadway friction are an essential requirement for an accurate collision reconstruction. This paper presents updated tire friction data for three grades (economy, touring, and performance) of commercially-available tires under both wet and dry road conditions. Differences between tires and road conditions were tested using 540 locked wheel braking tests with a single passenger vehicle on a single road surface over six consecutive days. The vehicle was braked from about 60 km/h to a stop using a mechanical brake actuator to minimize variations in brake pedal application. These results showed differences between the friction measured with economy, touring and performance tires under wet and dry road conditions. Dry road friction values were higher than those reported previously in the literature using older model tires and these dry road friction values were normally distributed. These data also showed that vehicle speed calculated using skid distance, even with improved estimates of skidding friction, underestimated pre-braking speed. To account for the pre-skid braking, adjustments to both the pre-skidding vehicle speed and onset of the driver's perception/response times appear to be warranted.

INTRODUCTION

An estimate of the friction coefficient between the tire and road surface during emergency or locked-wheel braking is an important assumption in the reconstruction of many motor-vehicle collisions. Most often, knowledge of the actual tire/road friction is unavailable. Because actual friction values vary with such factors as the specific tire, vehicle, road surface and environmental conditions [1,2], friction estimation in the reconstruction of a specific collision is not a trivial task. Studies of tire friction generally fall into two groups: general friction values with relatively broad ranges which are assumed to account for many factors which are either not known or not quantifiable in a specific reconstruction [2]; or specific friction values which apply to the exact tire and surface on which the measurements were acquired. The general friction values are used more commonly in collision reconstruction because actual road conditions often do not match test conditions and a larger range of friction coefficients is more conservative than a narrow range. Drag sled or actual skid tests are sometimes performed at the collision site in the belief that values so derived are accurate estimations of the actual values, or at least narrow the range of friction values used in the reconstruction. Often, however, these tests are conducted with different tires, with different vehicles, and on different days. Given these differences, it may be inappropriate to narrow the range of friction estimates on the basis of a few tests under dissimilar conditions.

In collision reconstruction analyses, the endpoints of the assumed range of friction coefficients are often used to compute the minimum and maximum vehicle speeds. Unfortunately, these minimum and maximum speeds provide little insight into the probability of these speeds relative to other possible speeds between the endpoints. With the increasing use of Monte Carlo methods in accident reconstruction [3,4], there is a need to define the statistical distribution of friction measurements as a way to appropriately model the friction distribution.

The primary goal of this study was to examine how friction coefficients vary amongst specific tire types and environmental conditions. Because other variables can potentially affect the friction at the tire/road interface, as many of these other variables as possible were controlled. Secondary goals of this study were to acquire sufficient data to adequately describe the statistical distribution of the measured friction values and to evaluate how some aspects of the test protocol affected the measured friction values.

METHODS

VEHICLE – All tests were conducted with a 1991 Honda Accord EX-R four-door sedan equipped with an automatic transmission. Prior to testing, the brake pads at all four disc brakes were replaced with stock Honda pads and burnished over 500 km of combined city and highway driving. The stock plumbing for the anti-lock brake system (ABS) was removed and a diagonal non-ABS system was installed. The left front (LF) and right rear (RR) brakes were supplied by the primary circuit of a new stock master cylinder and the right front (RF) and left rear (LR) were supplied by the secondary circuit. Two adjustable brake proportioning valves (Russell 5400, Daytona

Beach, FL), one for each circuit, were installed to control the rear brake hydraulic pressure. These valves were adjusted to ensure combined rear wheel lockup after front wheel lockup on dry roads. The flexible brake hoses at both front wheels were also replaced with braided steel hoses to reduce overall brake system compliance and thus ensure wheel lockup. Other minor vehicle modifications included removal of the rear seat to accommodate data acquisition equipment and removal of the rear spare tire and jack to accommodate other equipment. The vehicle's tested mass, with two occupants, was 1571 kg with 60 percent of the mass statically supported by the front wheels.

INSTRUMENTATION – Brake line hydraulic pressure was measured using four pressure transducers (Sensotec LM/2345-12, 3000 psig, Columbus, OH). Two pressure transducers were inserted into each diagonal circuit, one before and one after the pressure-reducing valve. This configuration provided brake line pressures at each of the four disc brakes. Wheel rotation sensors employed by the stock ABS system were used to monitor individual wheel rotation and lockup. Overall braking distance and vehicle speed were measured using a 5^{th}-wheel (MacInnis Engineering Associates, Richmond, BC). The 5^{th}-wheel was attached to the left rear wheel hub with a rotating bracket and a trailing arm to minimize the effect of vehicle pitch during braking.

An air-actuated piston installed in the driver's footwell and a regulated air supply installed in the trunk were used to apply the brake pedal in a repeatable manner for all tests. The actuator force and displacement were adjusted to match the brake-line hydraulic pressure response measured from five subjects (male and female). Each subject performed three emergency brake applications. The mean rise time of the left front brake line pressure to 2500 psi was 0.36 ± 0.01 s for the air cylinder and 0.40 ± 0.05 s for the human subjects (Figure 1). The rise time data acquired from the human subjects ranged from 0.28 to 0.56 s.

Two data acquisition systems were used. The data from the pressure transducers and wheel rotation sensors were acquired at 2000 Hz using a simultaneous-sample-and-hold data acquisition system (Win30DS, United Electronics Incorporated, Watertown, MA). Pressure transducer data was low-pass filtered at 600 Hz prior to acquisition. Anti-aliasing of the wheel speed sensor was not required at wheel speeds approaching zero, i.e., lockup. Fifth-wheel data were acquired at 1024 Hz using a quadrature encoder board (Tech80 5312B, Minneapolis, MN). Data from both DAQ systems were synchronized using a voltage signal from the brake light. Data were recorded for 5.0 seconds beginning about 0.5 seconds prior to brake application.

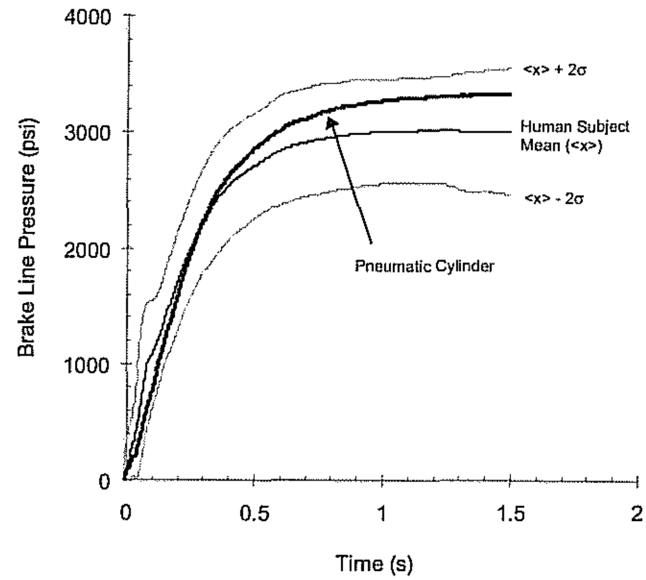


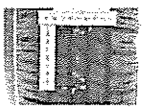
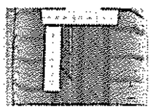
Figure 1. A comparison between the transient response of left front brake line pressure during brake pedal applications performed by human subjects (mean ± 2 standard deviations) and using the mechanical brake actuator.

TIRES – Three sets of new commercially-available radial tires were selected to represent three common tire grades: economy, touring and performance (Table 1). All tires were selected from the same parent manufacturer, although they have different brand names, as it was the intention of this study to compare tires of different grades and not tire manufacturers. Tire and rim sizes were chosen to match rolling circumferences. All tires underwent 150 km of combined city and coastal highway driving prior to testing.

Tire pressure was adjusted with the tires cold prior to each test block. The economy and touring tires were inflated to 30 psi for all tests except the first test day (W1) in which the economy tires were inflated to 34 psi. The performance tires were inflated to 29 psi for all tests. The inflation pressure was measured using a Bourdon Tube pressure gauge (Marsh PG-73, 160 psi, Newell, WV). Each tire was remounted at the same corner of the vehicle for all tests.

TEST SITE – The test site was located in rural Delta, British Columbia and consisted of a level stretch of asphalt about 15 years old with no visible wear or rutting. Traffic volume on this road was low. In qualitative collision-reconstruction terms, the surface was traveled asphalt, in fair to good condition and without defects. The aggregate varied from round to blocky with many flat surfaces exposed due to the age of the road (Figure 2). The cross slope of the road in the area of the testing was 2.2%.

Table 1. Description of tires tested.

Tire Grade	Economy	Touring	Performance
Description	Uniroyal Tiger Paw ASC	Michelin MX4 Rainforce	Michelin MXV4
Size	P185/70/R14	P185/70/R14	P195/60/R15
Load Index	87	88	88
Speed	S	T	V
Tread Wear	400	420	300
Traction	A	A	A
Temperature	C	B	A
Tread Plies*	1 PE + 1 Steel	1 PE + 2 Steel	1 PE + 1 PA + 2 Steel
Sidewall Plies*	1 PE	1 PE	1 PE
Tread Pattern			

*PE – polyester; PA - polyamide

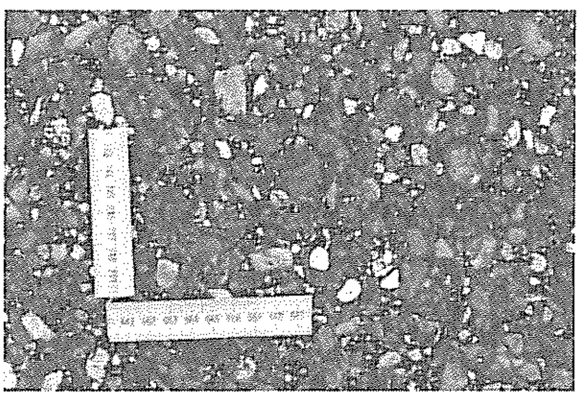


Figure 2. Asphalt test surface (ruler increment in cm).

Macrotexture of the surface was measured using an outflow meter [5]. This device consisted of a graduated plastic cylinder 95 mm (3.75 in) diameter above a base flange to which was fastened a neoprene ring 6 mm thick, 51 mm ID x 90 mm OD (1/4 x 2 x 3-9/16 in). The apparatus has a dry mass of 6.7 kg (14.8 lb) and the neoprene ring was 60 Durometer A hardness. The neoprene ring was placed in contact with the road surface and the cylinder was filled with water which then seeped out between the neoprene ring and the road surface. The time for the water level to fall from 203 mm to 102 mm (8 to 4 in) in the graduated cylinder was measured. Shorter times or higher flow rates indicated pavement surfaces with a high macrotexture, efficient texture shape for water flow, or both. Ten outflow tests were performed along the road. Five measurements were made along the middle of the visible left wheel track, 0.6 m from the centerline, and five measurements were made in the middle of the visible right wheel track, 2.0 m from the centerline.

The ASTM standard E 965-96 volumetric technique was also used to measure the surface macrotexture. This method involved spreading 30 ml of commercially available 60/80 mesh round glass spheres into a smooth circular patch on the road, measuring the diameter of the patch, and calculating the average texture depth. This was performed at five different locations on the right half of the test lane.

TEST PROCEDURE – Tests were conducted on six consecutive days in August, 1999. Environmental conditions obtained from a nearby weather station for these six test days are given in Table 2. Wet tests were conducted on the first, second and fourth test days and dry tests were conducted on the third, fifth and sixth test days. In the order they were conducted, test days were labeled W1, W2, D1, W3, D2 and D3. All three tire sets were tested each day and the test order was balanced across both wet and dry test days. One block of thirty tests was performed each day with each set of tires. This schedule yielded 3 blocks (90 tests) per day and 18 blocks (540 tests) over the entire experiment.

All tests were performed in one direction of travel over a 500 metre length of road. Dry tests began at the end of the test stretch and moved progressively toward the beginning to minimize overlap of previous skid marks. All wet tests were conducted on a single 50 m stretch at the end of the 500 m test section. On two days (W1 and W2), about 125 litres of water were applied over a 150 m² (3 m x 50 m) area every 20 minutes using a slow moving truck with a spray bar. The test vehicle rolled through the first 20 m of wet area and all tests were conducted in the last 30 m of wet area. On the third wet test day (W3), natural rainfall of 3.9 mm occurred over a four hour interval as measured at the test site. Manual wetting of the road surface as described earlier was required for the latter portion of the W3 test day. Descriptively, the road surface was thoroughly wetted for all wet tests and water spray from the tires was visible during all tests. There was no standing water on the road surface.

Table 2. Environmental conditions during test period of test days from local weather station (7).

Day	Temperature (°C) Minimum	Temperature (°C) Maximum	Precipitation (mm)
W1	16	22	0
W2	19	25	0
D1	20	22	0
W3	13	15	3.6*
D2	13	17	0
D3	14	19	0

* This rainfall occurred during the first portion of the test period. 1.2 mm of precipitation occurred before the test period.

For each test, the vehicle was accelerated by the driver to 60 km/h prior to entering the test section. Once in the test section, the accelerator pedal was released, the data acquisition systems were started and the brake actuator was manually triggered. The vehicle skidded to rest with the steering wheel held stationary by the driver. After each dry test, the distance (sSKID) from the start of the longest skid mark to the rear axle of the vehicle was measured using a fibre-reinforced cloth tape (Plumb 100ft/ 30m PL1730CME, CooperTools, Raleigh, NC) . There were no visible skid marks after the wet tests. The circumferential location of the contact patch on each tire was recorded to the nearest 16^{th} of a tire rotation (increments of 22.5 degrees). The vehicle was then reversed to the start position for the next test. Periodic charging of the air supply and road wetting resulted in 10 to 20 tests being conducted per hour.

Quasi-static drag tests were performed on wet and dry road surfaces to examine the difference between the friction values obtained from drag tests and dynamic skid tests. A spring scale was used to drag each tire and the draw force was visually noted and recorded. Ten tests were performed with two of each tire type, yielding 60 wet tests and 60 dry tests.

DATA ANALYSIS – Brake light activation was used to define the onset of braking and was designated as time zero. Vehicle speed at brake onset (vBRAKE) was computed from the 5^{th}-wheel data using finite differences. A line was fitted using least-squares to the speed data over the 250 ms immediately preceding brake onset. The test speed was then defined as the intersection of this best-fit line with the t = 0 axis, i.e., the intercept of the best-fit line. The total braking distance (sBRAKE) was the distance travelled by the 5^{th}-wheel between brake onset and rest. For a test speed of 60 km/h and a data acquisition rate of 1024 Hz, the resolution of the start point of this distance measurement was ±1.6 cm. Time to lockup of each wheel was determined from the wheel speed sensors and assumed to occur when the first wheel-speed sensor output dropped to zero. The distance travelled between lockup of the first tire and rest (sLOCK) was determined from the 5^{th} wheel data.

For this analysis, friction was defined as the average vehicle deceleration rate computed using Equation 1. As a result, the friction values were normalized for the small variations in pre-braking vehicle speed introduced by the test protocol. Three distinct deceleration rates were computed for each test: µBRAKE was defined as the average deceleration rate between onset of braking and vehicle rest using the vehicle speed at time zero (vBRAKE); µSKID was defined as the average deceleration rate based on the visible skid marks (for dry tests only) using the vehicle speed at the onset of skid marks (vSKID); and µLOCK was defined as the average deceleration rate based on sLOCK and the vehicle speed at lockup of the first tire (vLOCK). vSKID and vLOCK were determined from the 5^{th} wheel data.

$$\mu_i = \frac{v_i^2}{2gs_i} \quad (1)$$

STATISTICAL ANALYSIS – The primary independent variables in this study were tire type (economy, touring and performance) and road condition (wet and dry). The primary dependent variables in this study were the three deceleration rates (µBRAKE, µSKID and µLOCK). The null hypothesis was that there was no difference in tire friction, as quantified by these average friction values, between tire type and road condition. The null hypothesis was tested for each friction value using a two-way analysis of variance (ANOVA). Post-hoc comparisons were conducted using a Tukey Honest Significant Difference test. A significance level of 0.05 was used for these analyses. Differences between secondary dependent variables, such as the vehicle speeds and distance traveled, were also tested using a similar ANOVA. All statistical analyses were conducted using Statistica v5.1 software (Statsoft, Tulsa, OK).

The frequency of a specific tire orientation at rest was compared to the probability of this frequency occurring randomly using a binomial distribution. Since 12 independent tires were being assessed simultaneously, a Bonfer onni-adjusted significance level of 0.05/12 = 0.004 was used for this test. A three-way ANOVA was used to determine if a test order effect was present in the data. The dependent variables for this analysis were tire type (economy, touring and performance), road condition (wet and dry) and test day (1, 2 and 3). Since road watering occurred periodically rather than continuously, a paired t-test was conducted between the tests immediately before and after each watering cycle to assess whether this discrete watering technique affected the results.

Error bars on all figures refer to standard deviation of data and not standard error of the mean.

RESULTS

Ten water outflow tests to quantify the road surface macrotexture times yielded outflow times which ranged from 6.0 to 13.5 s (average = 9.7 ± 2.6 s). Measurements from the left and right wheel tracks were not significantly different.

The ASTM E965-96 road surface macrotexture tests yielded average patch diameters of 201 to 233 mm. The calculated mean texture depth ranged from 0.702 to 0.945 mm with an average of 0.823 mm.

The quasi-static drag tests revealed no overall difference between the wet and dry friction values (Figure 3). Within the wet drag tests, there was a significant difference between the economy and touring tires. There was no fference between the three tire sets under dry conditions and overall dry friction was 0.94 ± 0.06.

Data from 531 of the 540 skid tests were suitable for analysis. The pre-braking speed across all tests was 16.25 ± 0.43 m/s (58.5 ± 1.5 km/h). Both front and rear brake line pressures increased rapidly following brake onset (Figure 4). Front brake line pressures ramped up and reached a maximum of about 3200 psi. The rear brake line pressures deviated from the front brake line pressures at about 1000 psi and then reached a maximum of about 2000 psi (pressure reduction of about 38 percent). Both peak pressures and pressure rise profiles were highly repeatable across all tests.

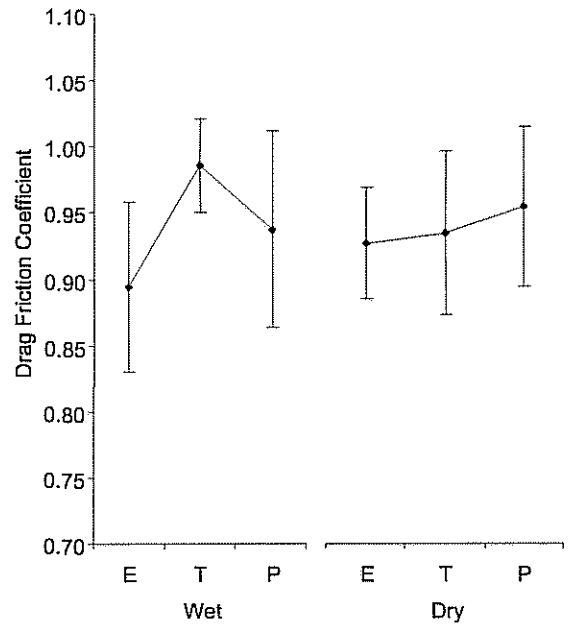


Figure 3. Tire friction from quasi-static drag tests under wet and dry conditions. (E – economy, T – touring, P – performance)

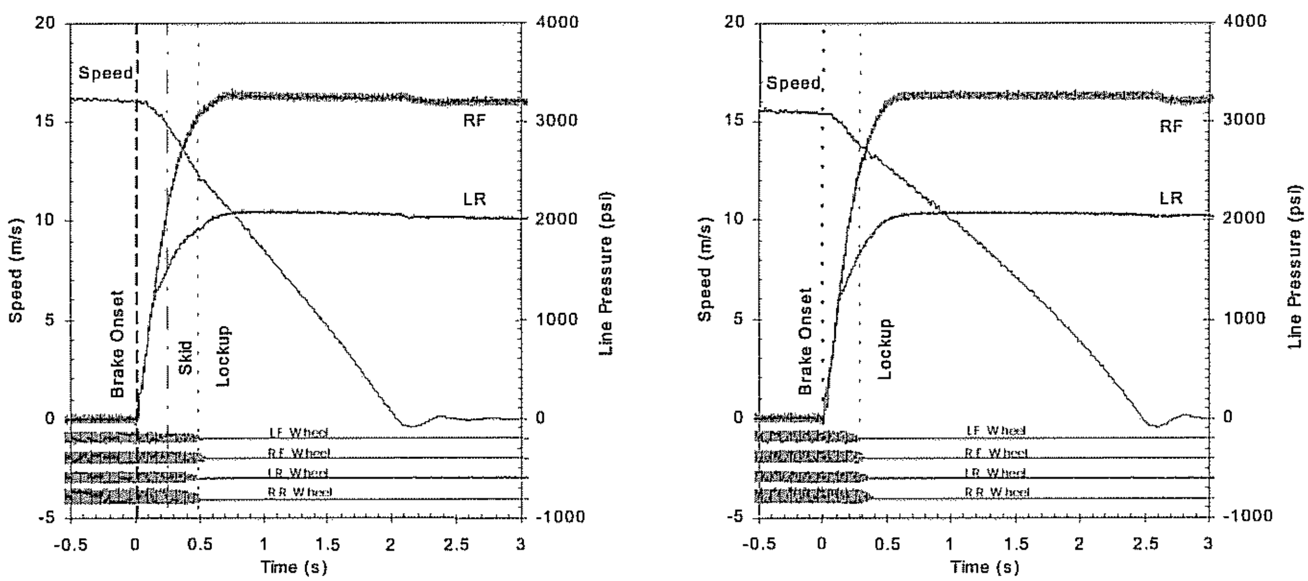


Figure 4. Exemplar data of dry (left) and wet (right) tests depicting vehicle speed, brake line pressures, and wheel lockup sensors. The vertical dashed lines depict the brake onset, the onset of skid marks, and lockup of the first wheel.

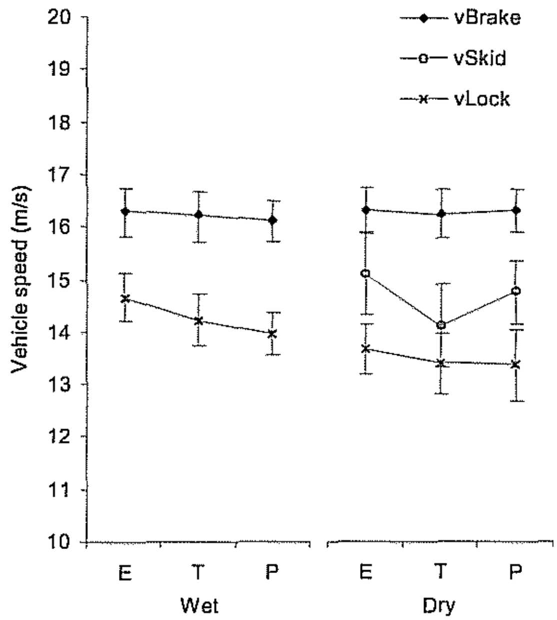


Figure 5. Vehicle speed at brake onset (vBRAKE), skid onset (vSKID) and first-wheel lockup (vLOCK) as a function of tire type and road surface conditions. (E – economy, T – touring, P – performance).

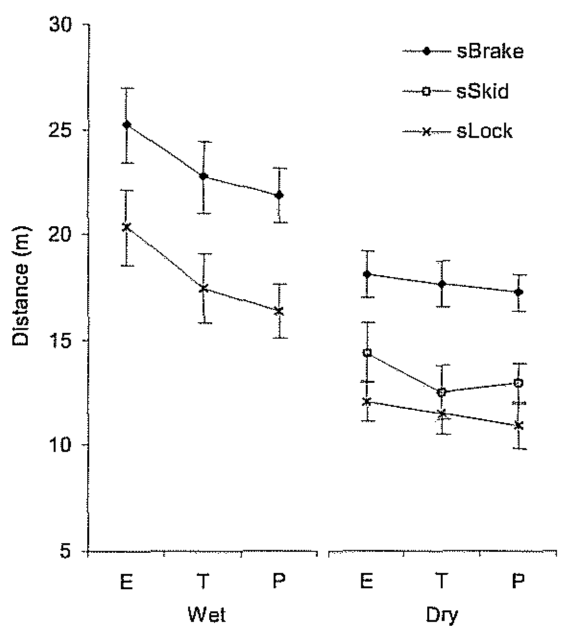


Figure 6. Distance to rest from brake onset (sBRAKE), skid onset (sSKID) and first-wheel lockup (sLOCK) as a function of tire type and road surface conditions. (E – economy, T – touring, P – performance).

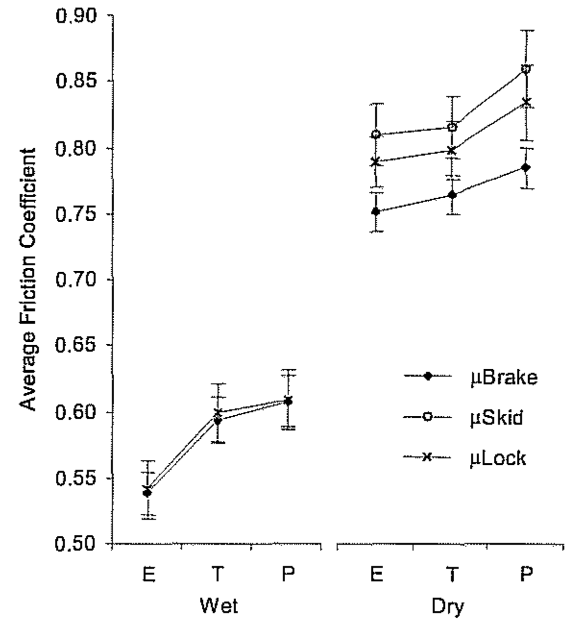


Figure 7. Average friction values based on brake onset (µBRAKE), skid onset (µSKID) and first-wheel lockup (µLOCK) as a function of tire type and road surface conditions. (E – economy, T – touring, P – performance).

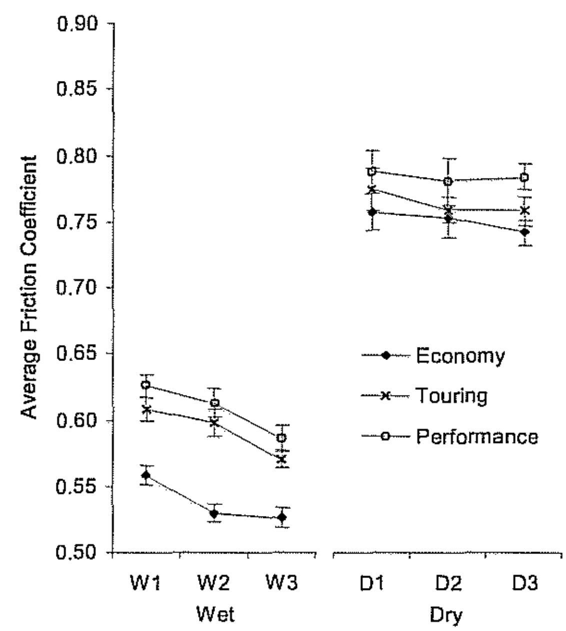


Figure 8. Average µBRAKE friction values as a function of test day, tire type and road surface conditions. (E – economy, T – touring, P – performance).

All four wheels locked in all tests. Except for the left rear tire, tire lockup occurred between 0.27 and 0.66 seconds (0.42 ± 0.07 s) after brake onset. On test days 5 and 6 (D2 and D3), the left rear tire occasionally locked as much as 2 seconds after brake onset. On other test days, it behaved like the other three tires. The right rear tire of the touring tire set locked more frequently than expected at one orientation ($p < 0.001$). Closer inspection of the data revealed that 11 of the 24 occurrences at this specific tire orientation occurred on the fourth and fifth tests days (W3 and D2). The other test days showed no increased incidence of locking at this tire position. No obvious flat spot was observed on the right rear tire at this location.

Only minor changes to the tire tread blocks were observed as a result of the wet skid tests. A saw-tooth wear pattern developed on the tread blocks of all three tire types after the first day of dry tests and was more prominent on the front tires than the rear tires. This pattern appeared to result from wear of the tread block during braking-induced deformation of the tread block and increased with the number of dry tests performed.

The test vehicle's speed was reduced between brake onset and both skid onset (measured only under dry conditions) and wheel lockup (measured under both wet and dry conditions) (Figure 4). Under dry conditions, average vehicle speed at onset of the longest skid mark was greater than vehicle speed at lockup of the first wheel (Figure 5). As a result, sLOCK was less than sSKID, and sSKID was less than sBRAKE (Figure 6). In all cases, a skid mark from one of the two rear wheels could be distinguished from the front wheel skid marks and were deposited before the front wheel skid marks. As a result, the skid distance recorded did not need to be adjusted for the vehicle wheelbase. Skid distance varied between 75 and 99 percent of braking distance and was significantly different between tires (Table 3). The kinetic energy was reduced by between 2 and 44 percent between brake onset and the onset of skid marks (Table 3). Lockup occurred earlier under wet conditions than under dry conditions and also occurred earlier for the economy tire than for the touring or performance tires (Figure 6).

Table 3. Mean and standard deviation (SD) for skid distance (sSKID) as a proportion of brake distance (sBRAKE), and the kinetic energy dissipated during the pre-skid interval (ΔKE) as a proportion of the total pre-braking kinetic energy (KE). (for dry tests only)

	sSKID/sBRAKE		ΔKE/KE	
	Mean	SD	Mean	SD
Economy	0.93	0.05	0.14	0.09
Touring	0.87	0.04	0.24	0.08
Performance	0.91	0.04	0.18	0.07
All	0.90	0.05	0.19	0.09

A significant difference in μBRAKE values was observed between wet and dry conditions and between all tires within each wet and dry condition (Figure 7). In both wet and dry conditions, μBRAKE was largest for the performance tire and smallest for the economy tire. The difference in μBRAKE values between tires was more pronounced under wet conditions. A similar pattern was observed for μLOCK (Figure 7), although there was no significant difference between the economy and touring tires under dry conditions. Under dry conditions, μSKID was significantly larger for the performance tire than for either the economy or touring tire. A comparison amongst the three average friction coefficients showed that under dry conditions, μSKID yielded the highest values for all tires, followed by μLOCK and then μBRAKE. Under wet conditions, there was no difference between μLOCK and μBRAKE friction values.

The μBRAKE friction data were then separated by tire and analyzed for day effects (Figure 8). For the economy tire, this analysis revealed a 0.03 decrement in μBRAKE between the sequential W1 and W2 test days (both of which were artificial wet days). A 0.015 decrement in μBRAKE was noted between the last two tests days (both dry days). For the touring tire, μBRAKE was reduced by about 0.01 between the W1 and W2 test days, followed by a larger decrement of about 0.04 between the W2 and W3 test days. A small decrement (<0.02) was noted between the D1 test day and the other two dry test days (D2 and D3). The pattern of the performance tire under wet conditions was similar to the touring tire. There was no difference in the μBRAKE friction values across the three dry test days for the performance tire.

The watering protocol was another potential source of variation between sequential tests on tests days 1 and 2 (W1 and W2). Analysis of the tests immediately before and immediately after watering showed that pre-watering μBRAKE values were 0.005 ± 0.010 higher than post-watering values ($p < 0.01$).

DISCUSSION

In this study, the skidding performance of three commercially-available radial tires was examined under wet and dry road conditions. Tests were conducted on a single road surface to focus on tire type and eliminate the confounding influence of road type. A mechanical brake actuator was also used to eliminate variations in the brake application profile which occurs with human subjects. This controlled test protocol, together with the large number of tests conducted in each cell of the study matrix, revealed a number of statistically significant differences amongst the three tires, two road conditions and the three measures of friction used to quantify these data.

The current data demonstrated that wet friction values were lower than dry friction values, a finding that has been previously observed by others [1,2]. The data also showed increased friction with improved tire grade for all three friction measures. Although Wallingford et al. [6] have previously observed increased friction with performance tires, the current data extends these findings in two ways. First, these data showed increased friction with increased tire grade under both wet and dry conditions. Second, the observed friction difference between tires was greater under wet conditions than under dry conditions, particularly for the economy tire.

Average, rather than instantaneous, values for the coefficient of friction were used in this study because these values are more commonly used in the analysis of real collisions. Under dry conditions, vehicle deceleration was relatively constant and an average measure of vehicle deceleration appeared to be valid. Under wet conditions, there was a distinct increase in the deceleration rate as vehicle speed approached zero (Figure 4). The source of this increased deceleration is not known, however it may be related to an increased ability for the tire to disperse water on the road surface at lower speeds.

From an collision reconstruction perspective, the most relevant friction measure is µSKID. In this study, µSKID data were only acquired under dry road conditions. Although there were statistically significant differences between the µSKID values across the three tires tested, the overall range of friction values was relatively narrow. Across all three tires, µSKID varied between 0.75 and 0.93. Moreover, the overall distribution of µSKID was similar to the normal distribution with a mean and standard deviation of 0.828 ± 0.033 (Figure 9). This range of dry skidding friction values is higher than that reported in some standard friction references [1,2]. The current data, however, were acquired using newer model tires and may therefore better represent the level of friction achievable with modern automobile tires.

The dry friction values obtained from the quasi-static drag tests (0.94 ± 0.06) were greater than the dry friction values obtained from the dynamic skid tests (0.828 ± 0.033). The difference between the wet drag test values (0.94 ± 0.07) and the overall wet dynamic tests (µBRAKE = 0.579 ± 0.035) was even greater. Both results suggest that quasi-static drag tests using the actual tires on the actual road surface provide a poor estimate of the friction available during actual skidding.

During the dry test days, the skid marks produced by the tires began as light marks, or shadow skids [1,2], and gradually darkened as they neared the stopped position of the vehicle. As has been observed by others, skid marks were deposited before the first wheel locked up [8,9,10]. As the tire rotation slowed, the relative slip between the tires and the road increased and the skid marks became darker. The time from the brake application to the onset of visible skid marks on the road has been defined previously as the transient period of the braking process [11]. The transient brake period in the current study was between 0.082 and 0.540 s (0.28 ± 0.09 s). Using a 1989 Toyota Camry, Neptune et al. [11] reported minimum transient brake periods of between 0.11 and 0.25 s for differing road types. The current minimum times are within the range reported by these authors, however, the mean transient brake times observed in the current study are slightly longer than these previously reported values.

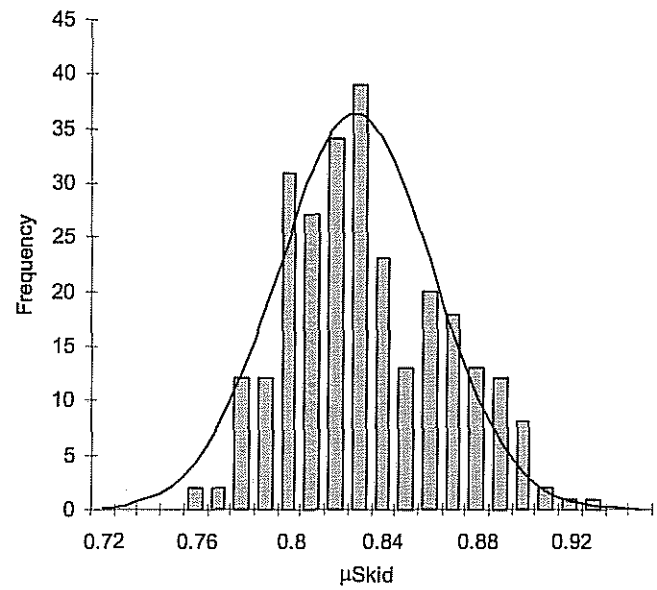


Figure 9. Distribution of µSkid values for all three tire sets under dry road conditions with a superimposed normal distribution (0.828 ± 0.033).

The current data indicated that the vehicle speed was reduced by 1 to 25 percent and kinetic energy was reduced by 2 to 44 percent between brake onset and skid onset. These results indicated that an estimate of a vehicle's pre-braking speed based solely on the skid marks underestimates the vehicle's actual pre-braking speed by 10 ± 5 percent. If µSKID friction values lower than 0.828 ± 0.033 were used in the calculation, the vehicle's pre-braking speed would be further underestimated. Neptune et al. [11] have proposed that a ramp acceleration over the pre-skid interval be added to the skid distance to account for the post-braking, pre-skidding speed reduction. Using the current data set, we compared the actual pre-braking vehicle speed (vBRAKE) with the speed predicted by this proposed technique. The actual values of vSKID, µSKID and the transient brake times for each test were used to generate a test-by-test comparison over the 270 dry tests conducted with all three tire sets. This analysis revealed that the method proposed by Neptune et al. [11] underestimated the actual pre-braking vehicle speed by 3.0 ± 3.0 percent. These results suggest that the proposed method is valid for dry roads.

Since skid distances are rarely available for wet roads, the proposed technique was not evaluated for wet friction. However, given that the average friction on wet roads was similar from both brake onset (µBRAKE) and locked-wheel onset (µLOCK) (Figure 7), a ramped acceleration will likely underestimate the pre-braking speed. The current data suggests that a step rise in acceleration, rather than a ramp, is appropriate for treating pre-skidding intervals on wet roads.

The time lag between onset of braking and onset of skid marks has another implication when collision avoidance analyses are being conducted. Perception/response times are typically assumed to end at the onset of skidding [12]. The current data indicated that the skid marks begin 0.28 ± 0.09 s after brake application. In addition to adjusting the vehicle speed for this period of pre-skid braking, the perception/response interval should also be adjusted to end at the onset of braking rather than the onset of skidding.

Many friction studies aimed at assisting the collision reconstruction process have not quantified their road surfaces in an objective way [6,8,9,10]. We attempted to quantify the macrotexture of our road surface by using a water outflow technique and a glass sphere deposition technique. While the water outflow method is more objective than a description of the surface, water outflow rates depend on the pavement surface macrotexture as well as the dimensions, weight and fluid volume of the test device. There has been no standardization of outflow meters [5,13] so outflow times can only be compared to other results using the same meter. Six concrete and eight asphalt surfaces were previously tested at two NASA Research and Flight Centers using the same meter design [5]. The outflow times reported were 13.2 to 158 seconds for concrete and 1.8 to 83.5 seconds for asphalt. Outflow times at our test site were less than previously reported for concrete but within the lower end of the range for asphalt.

Both the analysis for day effects and the analysis for pre- and post-watering effects showed that there were small systematic errors introduced by the protocol used for this study. Although the µBRAKE friction values remained relatively constant over the three dry test days, µBRAKE values declined over the three wet test days for all three tires types. The pattern of decline, however, was different for the economy tire than for the other two tires. The larger drop in the friction value for the economy tire occurred between the first and second test days (W1 and W2). Since both days were artificial wet days and had similar daytime temperatures, environmental variables are not a likely explanation for this difference. Tire wear may explain this decrement, however, this implies that the economy tires wear more rapidly than the touring or performance tires. Specific measures of tire wear were not made and therefore this explanation cannot be confirmed.

The touring and performance tires demonstrated a larger decrement in friction values between the second and third wet days (W2 and W3). Although this decrement may also be related to tire wear, natural rain during the third wet day (W3) may also have affected tire performance. The natural rain did not last all day and only the touring and performance tires were tested under the natural rain conditions in which the run-up area prior to the skid testing area was also wet. This wet run-up may have resulted in cooler, and possibly wetter, tires and therefore the observed difference may be related to environmental factors rather than tire wear.

Although a statistically significant difference between the pre- and post-wetting friction values was observed, the absolute values of this difference was less than one percent of the measured wet friction values. Based on this small absolute size, the periodic wetting of the road surface appears to be a valid method of simulating wet road conditions. Given the difference between the artificial and natural wet road conditions observed with the touring and performance tires, however, we recommend that the run-up stretch of road, in addition to the actual test area, also be wetted for future testing.

LIMITATIONS – These experiments were conducted using a single vehicle on a single section of road using only three different tires types. Vehicle characteristics have previously been shown to affect friction using the same tires and road surface [9]. Similarly, different road surfaces have been reported to produce different friction coefficients [2]. Our results have shown that different tire types result in different friction coefficients. Hence, the narrow range of friction coefficients reported here must be used cautiously when reconstructing collisions in which different vehicles, road surfaces and tires are involved.

Our limited tests of human subjects showed that the rate of brake pressure rise varies between individuals (Figure 1). Although the mechanical actuator provided repeatable brake applications, it does not represent the range of brake application rates that might exist in the motoring public.

CONCLUSIONS

These experiments have demonstrated that tire friction varies amongst economy, touring and performance tires under both wet and dry road conditions. The data also demonstrated that the dry road friction values of modern automobile tires are higher than those reported in past literature using older model tires and that these friction values are normally distributed. These data have shown that vehicle speed calculated using skid distance, even with improved estimates of skidding friction, underestimate a vehicle's pre-braking speed. To account for the pre-skid braking, adjustments to both the pre-skidding vehicle speed and onset of the driver's perception/response times appear to be warranted.

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