Experimental Investigation of the Transient Aspect of Hydroplaning

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When a nonrotating tire moves from a quasi-dry section to a flooded section of a pavement, a transition from a nonhydroplaning to a hydroplaning state may occur. During this transition, friction force drops from a higher level to a lower level. This transition phenomenon was investigated experimentally. The experimental program was conducted both in the laboratory on a moving-belt friction tester and on the highways at the Pennsylvania Transportation Institute Research Facility. Good agreement was found between the laboratory and the highway test results. The results showed that the transition time could last up to 65 ms under the limits of operating conditions employed in the test program. The operating conditions included the test speed, the water-film thickness, the tire-inflation pressure, the vertical load on the tire, and the microtexture of the pavement.

When a film of water on a pavement is of sufficient thickness, the vehicle may hydroplane; i.e., the tires may be separated from the pavement by the water wedge formed between the tire surface and the pavement surface.

When a tire rolls or slides on a water-covered pavement at a velocity well below that at which hydroplaning occurs, most of the water is displaced from the contact region between tire and pavement by means of a forward and a lateral spray. The resulting change in momentum of the fluid creates hydrodynamic pressure that reacts on the surfaces of both pavement and tire. The force from hydrodynamic pressure increases as the square of the velocity, and also, as the velocity increases, the fluid inertia effects tend to retard fluid escape from the contact region between tire and pavement. The fluid wedge, which forms at the leading edge of the contact with the pavement, now becomes thicker and begins to penetrate farther into the contact region, so that part of the tire becomes supported by a progressively thicker water film. As the velocity increases further, the force from hydrodynamic pressure developed under the tire eventually exceeds the total vertical force and the tire will lift completely off the pavement. The lowest velocity at which this occurs is called the critical hydroplaning speed.

TRANSIENT ASPECT OF HYDROPLANING

The friction force developed by a tire will vary with time if the tire encounters water films of changing thickness along its path. Pavement unevenness causes the formation of random puddles on the pavement surface during precipitation. The unevenness may be the result of compaction by vehicular traffic on flexible pavements. Large temperature variations may cause the development of undulations in the pavement that create both longitudinal and transverse puddles.

The probability is large that skidding produced by moments about the yaw axis will occur because of differential braking or cornering forces developed when all the tires do not hydroplane. The question therefore arises whether hydroplaning occurs as soon as the tire encounters a deep puddle or only after a finite time interval has elapsed. This question leads to another: Is there a relationship between the puddle length and depth and the delayed response time (or transient duration)?

A large amount of work, both experimental (1,2) and analytical (3,4), has been done on the problem of hydroplaning, although exclusively for the case of a constant water layer on the pavement. The present research was necessary to determine whether there is a minimum puddle length that can exist on a pavement without creating a potential hazard to automotive traffic from temporary hydroplaning.

EXPERIMENTAL PROGRAM

The experimental program was designed to conduct tests by using full-scale passenger car tires both in the laboratory and on the highway. The operating variables were closely controlled in the laboratory, and the testing on the highways was done under prevailing highway and environmental conditions. In the entire test program the effects of the following variables were investigated:

1. Tire-inflation pressure,
2. Tire vertical load,
3. Sudden change in water-film thickness,
4. Magnitude of the sudden change in water-film thickness,
5. Surface texture,
6. Vehicle speed, and
7. Viscosity of water (by changing the temperature of water).

LABORATORY TEST PROGRAM

The laboratory test apparatus, henceforth called the moving-belt friction tester (MBFT), consists of an endless belt that runs on two steel drums. The roles of tire and pavement are reversed in the laboratory; i.e., the wheel that carries the test tire is held stationary in space, whereas the "pavement" moves relative to the fixed tire. The pavement is represented by a thin stainless-steel belt. The drums are supported on a rigid frame by means of four bearings. A flat Teflon plate under the belt supports the loaded tire. Figure 1 shows a schematic of the MBFT, and Figure 2 shows the tire-belt contact region. [Figures 1 and 2 are from Agrawal (5).] One drum is driven by an automotive engine, and belt tangential speeds of up to 110 km/h (70 miles/h) can be attained. The water-delivery system can provide a film thickness of up to 2.5 mm (0.1 in).

During each test the belt was sprayed with a thin film of water to represent quasi-dry conditions. A sudden change in the water-film thickness on the belt was brought about by engaging the water pump to the driving engine via a clutch. High-speed motion pictures of the flow through the nozzle showed that approximately 5-8 ms elapsed between the clutch engagement and the discharge through the nozzle. During this period, intermittent water jets were ejected from the nozzle. These water jets hit the tire surface and were deflected to the sides. It was noted that the friction force did not vary from the value at the quasi-dry condition, which indicated that the transient duration was not affected by these water jets.

The MBFT is instrumented to measure the following quantities:

Figure 1. Details of MBFT.

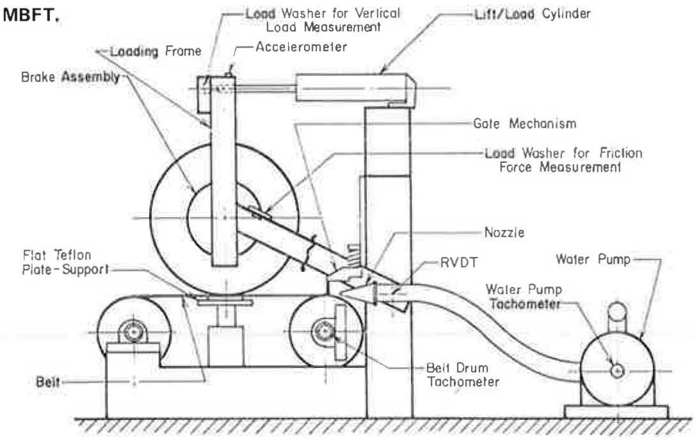
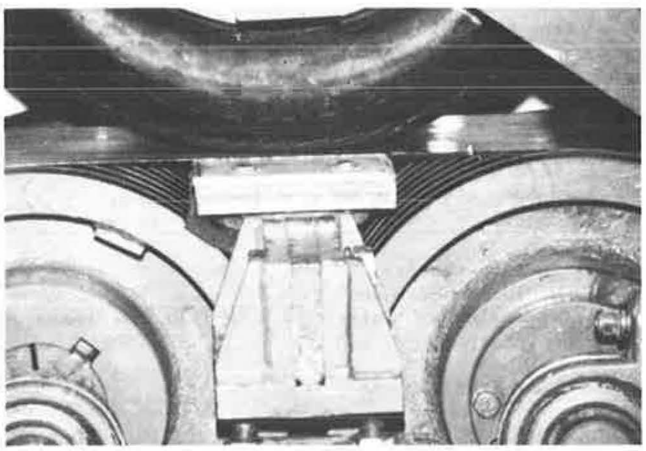


Figure 2. Belt support system and circumferential grooves on drums of MBFT.



1. Vertical force on the tire,
2. Friction force at the tire-belt interface,
3. Rotational speed of the water pump, and
4. Vertical motion of the tire center.

In addition, a microswitch lever was placed ahead of the nozzle to indicate the precise instant of the impact of the thick film of water on the tire surface.

The following test conditions were selected:

1. Locked (completely braked) test tire,
2. Smooth bias-ply tire [approximately 0.66 m (26 in) in diameter] from which the tread was removed mechanically,
3. Tire-inflation pressure of 120-207 kPa (18-30 lbf/in^2),
4. Tire vertical force of 2000 N (450 lbf),
5. Belt speed of 48-110 km/h (30-70 miles/h),
6. Flow rate of water of 380-760 L/min (100-200 gal/min),
7. Water temperature of 10°C (50°F) and 35°C (95°F), and
8. Fine-textured belt (metallic spray coating).

The friction force at the tire-belt interface is represented as the brake-force coefficient (BFC), defined as follows:

$$\text{BFC} = [(\text{friction force})/(\text{vertical force})] \times 100 \qquad (1)$$

Test Procedure

A complete test sequence required two operators and consisted of the following steps:

1. Apply the brake to keep the tire from rotating;
2. Preselect the vertical force and adjust the pneumatic pressure in the loading cylinder;
3. Adjust the tire-inflation pressure;
4. Obtain the preselected belt speed;
5. Apply the thin film of water on the moving belt to simulate quasi-dry condition;
6. Bring the tire down on the belt and apply the vertical force;
7. Start the recording equipment;
8. Engage the clutch to supply thick water film;
9. Lift the tire, stop the belt, and disengage the water pump; and
10. Stop the recording equipment.

Test Results and Discussion

The typical force-time history as the tire encountered a sudden change in the water-film thickness is shown in Figure 3. To describe the response of the tire to the change in film thickness, three time periods are defined, as follows: τ_1, the time to reach the first steady-state friction (BFC) value; τ_2, the time to reach minimum friction value; and τ_3, overall time of the transient.

Total hydroplaning in the laboratory tests was indicated by a small BFC value. The final available BFC for total hydroplaning is very small (typically less than 5 percent of the vertical force, or a friction coefficient of 0.05). Under a total hydroplaning condition, the tire is completely separated from the pavement. Whether one actually achieves total hydroplaning depends on the thickness of the water film, the speed, the texture of the surface, the condition of the tire, and other operating variables. In fact, since the operating conditions were varied in the tests, hydroplaning in the final state did not always occur. However, even when the final state is not one of total hydroplaning, the nature of the response is the same and can be described by the same three characteristic times. The operating conditions tested are described in Table 1.

Table 2 shows the effects of tire-inflation pressure, water-flow rate, and water temperature on the transient times. Under each set of operating conditions, the testing was conducted in an increasing order of belt speed. It can be seen that the increase in speed under a fixed set of other

Figure 3. Typical force-time history.

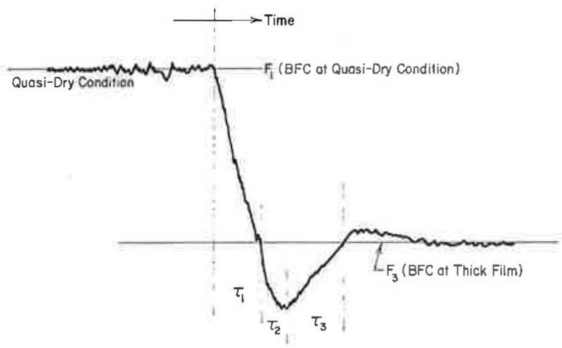


Table 1. Operating conditions for laboratory tests.

Test	Tire-Inflation Pressure (lbf/in²)	Flow Rate (gal/min)	Water Temperature (°F)
2A-C	24	184	50
3A-E	18	128	50
4A-D	18	184	50
5A-D	35	128	50
6A-C	24	194	50
7A-E	18	136	50
8A-D	18	200	50
10A-C	18	185	95
11A-C	18	172	95
12A-D	24	200	95
13A-D	18	128	95

Notes: 1 lbf/in² = 6.8 kPa; 1 lbf = 4.4 N; 1 gal/min = 3.8 L/min; t°F = (t°C ÷ 0.55) + 32.
For all tests, tire vertical load was 440 lbf, and a belt that had a textured surface was used.

operating conditions does not show a significant variation in the three transient-time durations.

The gross effects of changing flow rates, viscosity, and inflation pressure are investigated in Table 3, which shows the average values of the transients for each set of test conditions. Test group A consists of tests 10 A-C, 11 A-C, and 13 A-D. No significant variation or trend is identifiable in the average transient durations of τ_1, τ_2, and τ_3. Group B represents similar results when the water temperature (hence viscosity) was changed. Again no significant variation or trend is identifiable. Group C represents the effect of viscosity change in which the effect of flow rates (groups A and B) is insignificant. Again the transient-time durations are very close. The last row in Table 3 represents the combined effect of all the operating variables. It can be seen that the magnitudes of τ_1, τ_2, and τ_3 are all of the same order when compared with the corresponding durations in each of the other test groups. Thus it can be concluded that the transient durations or the response times are not sensitive to changes in operating variables.

Referring again to Table 2, it should be noted that, in each test series, the steady-state value of the BFC in the flooded region (F_3) decreases with increasing speed. This trend is well documented for highway testing (6). However, whereas in the highway testing the film thickness on the pavement remains constant for a series of tests in which the speed is increased gradually from one test to another, the film thickness in the laboratory changes when belt speed is increased if the water-flow rate remains constant. If the changes in the film thickness during a test series are ignored, the laboratory tests show the trend documented earlier (6).

HIGHWAY TEST PROGRAM

The Pennsylvania Transportation Institute road friction tester (Mark 3) (7) was the principal test apparatus. It is equipped with a six-component force-and-torque measurement system.

The tester has a single wheel. The trailer consists of a frame, a passenger car brake-and-wheel assembly, a rod that retains the brake plate (otherwise free to rotate), and an air cylinder for providing normal force on the tire. The wheel spindle is mounted rigidly to the main frame, and the frame is connected by pitch-and-yaw pivots to the hitch of the towing vehicle.

To obtain a sudden change in the water-film thickness in the path of the tire, water was discharged on the pavement in the lateral direction to create a flooded or thick-film region and to mildly wet the pavement section outside the flooded region. Figures 4 and 5 show the tester and the preparation of the test site. Figures 6 and 7 show a distinct step change in the film thickness and the tester in operation.

The tester is instrumented to measure the following quantities: (a) longitudinal forces at the tire-pavement interface, (b) vertical force on the tire, and (c) vehicle speed.

The water-film thickness on the pavement was measured by using a National Aeronautics and Space Administration water-level-depth gauge. In addition, a microswitch was installed on the tester to indicate the precise instant that the test tire comes in contact with the line of sudden change in water thickness.

The following test conditions were selected:

1. Locked (i.e., completely braked) test tire,
2. ASTM standard E524 tire,
3. Tire-inflation pressure of 120-270 kPa (18-30 lbf/in²),
4. Tire vertical force of 1780-4450 N (400-1000 lbf),
5. Vehicle speed of 40-96 km/h (25-60 miles/h),
6. Water-film thickness of 1.27-6.35 mm (0.05-0.25 in), and
7. Pavement texture of 0.38-0.76 mm (0.015-0.03 in).

When a desired film thickness was attained on the pavement, repeated tests were conducted by using increasing vehicle speeds. The highest speed of test was limited by either the available approach length or the minimum drag force attainable on a particular pavement surface. A series of tests was performed by using different combinations of operating conditions.

Test Results and Discussion

The typical force-time history in the highway tests (Table 4) was similar to that in the laboratory test program.

Table 5 shows the effect of the various test parameters on the transient-time durations (τ_1, τ_2, and τ_3) and on the friction force. C2, C3, and C5; D1-D10; and J1-J4, J6-J12, and J16-J19 in Table 4 refer to data obtained on portland cement concrete (PCC), Jennite, and bituminous concrete surfaces (ID2A), respectively. The surfaces differ in method of construction, material used, and available texture.

Total hydroplaning condition in the highway test program was identified by a small value of BFC, as was done in the laboratory tests. The reason for

Table 2. Laboratory-test results on a textured belt.

Belt Speed (miles/h)	Transient Time (ms) τ_1	τ_2	τ_3	BFC F_1	F_2	F_3	Distance (ft) d_1	d_2	d_3
Tests 2A-C									
43	2.0	5.9	42.0	18.2	–	6.8	0.13	0.37	2.65
46	3.9	7.8	–	18.2	–	5.7	0.26	0.53	–
49	3.0	6.8	33.2	17.0	–	4.6	0.21	0.48	2.39
Avg	3.0	6.8	37.6						
Tests 3A-E									
28	9.7	15.6	27.3	27.3	–	17.0	0.40	0.64	1.12
36	8.8	14.6	27.3	20.5	–	10.2	0.47	0.77	1.47
39	5.9	9.8	27.3	21.6	–	8.4	0.34	0.56	1.56
44	4.9	9.8	31.3	18.2	–	6.8	0.32	0.63	2.02
48	5.9	8.8	25.4	19.3	–	5.7	0.41	0.62	1.80
Avg	7.0	11.7	27.7						
Tests 4A-D									
34	3.9	–	–	18.2	–	9.1	0.20	–	–
40	–	–	–	13.6	–	6.8	–	–	–
45	5.9	11.7	31.3	21.6	–	4.6	0.39	0.78	2.06
50	5.9	7.8	21.5	18.2	–	2.3	0.43	0.57	1.58
Avg	5.2	9.8	26.5						
Tests 5A-D									
30	7.8	14.7	27.3	30.7	–	18.2	0.35	0.65	1.20
38	2.9	6.9	12.7	20.5	–	8.0	0.16	0.38	0.71
44	10.7	16.6	25.4	19.3	–	7.9	0.69	1.10	1.64
48	2.9	8.8	–	18.2	–	5.7	0.21	0.62	–
Avg	6.1	11.5	21.8						
Tests 6A-C									
30	9.8	17.6	47.9	38.6	–	19.3	0.43	0.77	2.11
42	11.7	18.6	39.1	15.9	–	6.8	0.72	1.14	2.40
52	4.9	9.8	15.6	27.3	–	2.3	0.37	0.75	1.19
Avg	8.8	15.3	34.2						
Tests 7A-E									
34	2.9	7.8	15.6	27.3	–	11.4	0.15	0.39	0.78
38	2.9	7.8	13.7	19.3	–	7.9	0.16	0.44	0.76
42	5.9	12.7	–	19.3	–	9.1	0.36	0.78	–
44	9.8	16.6	22.5	18.2	–	5.7	0.63	1.07	1.45
50	8.7	10.7	15.7	15.9	–	3.4	0.64	0.78	1.15
Avg	6.1	11.1	16.9						
Tests 8A-D									
30	9.8	14.7	31.3	30.7	–	10.2	0.43	0.65	1.38
38	8.8	13.7	17.6	19.3	–	5.7	0.49	0.76	0.98
42	4.9	8.7	17.6	15.9	–	4.6	0.30	0.60	1.08
50	9.8	13.7	20.5	20.5	–	2.27	0.72	1.00	1.50
Avg	8.3	12.7	21.8						
Tests 10A-C									
34	5.8	9.8	31.3	18.2	–	11.4	0.30	0.49	1.60
42	5.9	11.7	30.3	11.4	–	3.4	0.36	0.72	1.90
48	9.8	19.5	28.3	8.0	–	0	0.69	1.38	2.00
Avg	7.2	13.7	30.0						
Tests 11A-C									
32	–	–	–	19.3	–	9.1	–	–	–
49	4.9	9.8	16.6	12.5	–	4.5	0.35	0.70	1.20
51	9.8	16.6	22.5	6.8	–	2.3	0.73	1.20	1.70
Avg	7.4	13.2	19.6						
Tests 12A-D									
32	7.8	16.6	19.5	20.5	–	12.5	0.37	0.78	0.92
38	6.8	9.8	17.6	18.2	–	9.1	0.38	0.54	0.98
42	–	–	–	15.9	–	8.0	–	–	10
48	3.9	7.8	15.6	13.6	–	4.6	0.30	0.60	1.10
Avg	6.2	11.4	17.6						
Tests 13A-D									
29	3.9	8.8	23.4	25.0	–	17.0	0.17	0.37	1.00
36	5.9	12.7	21.5	15.9	–	10.2	0.31	0.67	1.13
45	7.8	15.6	22.5	12.5	–	5.7	0.52	1.03	1.48
52	7.8	16.6	22.5	11.4	–	3.4	0.60	1.27	1.71
Avg	6.4	13.4	22.5						

Notes: 1 mile/h = 1.6 km/h; 1 ft = 0.33 m.
Dash indicates that data cannot be interpreted.

Table 3. Summary of laboratory-test results.

Test Group	Operating Condition Changed	Categories Compared	Average Transient Times (ms) τ_1	τ_2	τ_3	Conclusion
A	Flow rate (lower viscosity, low inflation pressure)	10A-C	7.2	13.7	30.0	No significant variation or trend
		11A-C	7.4	13.2	19.6	
		13A-D	6.4	13.4	22.5	
		Avg	7.0	13.4	24.0	
B	Flow rate (higher viscosity, low inflation pressure)	4A-D	5.2	9.8	26.5	No significant variation or trend
		8A-D	8.3	12.7	21.8	
		7A-E	6.1	11.1	16.9	
		3A-E	7.0	11.7	27.7	
		Avg	6.7	11.3	23.2	
C	Flow rate (higher viscosity, higher inflation)	2A-C	3.0	6.8	37.6	Small variation in τ_1 and τ_2
		6A-C	8.8	15.3	34.2	
		Avg	5.9	11.1	35.9	
D	Viscosity (similar flow rates, higher inflation pressure)	12A-D	6.2	11.4	17.6	No significant variation
		6A-C	8.8	15.3	34.2	
		Avg	7.5	13.4	25.9	
E	Viscosity	A	7.0	13.4	24.0	
		B	6.7	11.3	23.2	
		Avg	6.9	12.4	23.6	
	Inflation pressure	C	5.9	11.1	35.9	
		E	6.9	12.4	23.6	
	Combined effect	All	7.4	11.2	29.6	

Note: 1 gal/min = 3.8 L/min; 1 lbf/in^2 = 6.8 kPa.

using this criterion was the fact that the transient-time durations did not show a significant variation with speed under any set of operating conditions (Table 3).

Figure 4. Mark 3 friction tester.

Figure 5. Preparation of test site.

To compare the effects of various parameters, the results from Table 5 are summarized in Table 6. Since the effect of vehicle speed can be ignored for each set of operating conditions (water-film thickness, tire-inflation pressure, vertical force, and texture depth), average values of the three transient-time durations are computed. The effect of water-film thickness, tire-inflation pressure, and

Figure 6. Distinct step change in film thickness.

Figure 7. Mark 3 friction tester during a test.

Table 4. Operating conditions for highway tests.

Test	Water-Film Thickness (in)	Tire-Inflation Pressure (lbf/in^2)	Tire Vertical Load (lbf)	Pavement Characteristics: Surface Description	Pavement Characteristics: Texture Depth (in)	Skid No.
C2	0.075	30	800	PCC	0.018	36
C3		18	800	PCC	0.018	36
C5		24	800	PCC	0.018	36
D1	0.06	18	800	ID2A	0.030	57
D2		24	800	ID2A	0.030	57
D3	0.15	24	800	ID2A	0.030	57
D4		18	800	ID2A	0.030	57
D5	0.25	18	800	ID2A	0.030	57
D6		24	800	ID2A	0.030	57
D7		14	800	ID2A	0.030	57
D8	0.85	18	800	ID2A	0.030	57
D9		24	800	ID2A	0.030	57
D10		30	800	ID2A	0.030	57
J1	0.055	24	800	Jennite	0.015	16
J2		30	800	Jennite	0.015	16
J3		18	800	Jennite	0.015	16
J4		18	400	Jennite	0.015	16
J6		24	400	Jennite	0.015	16
J7	0.075	24	800	Jennite	0.015	16
J8		30	800	Jennite	0.015	16
J9		18	800	Jennite	0.015	16
J10		18	1000	Jennite	0.015	16
J11	0.10	30	800	Jennite	0.015	16
J12		24	800	Jennite	0.015	16
J16		24	1000	Jennite	0.015	16
J17	0.25	24	800	Jennite	0.015	16
J18		18	800	Jennite	0.015	16
J19		30	800	Jennite	0.015	16

Note: PCC = portland cement concrete; ID2A = bituminous concrete.

Table 5. Highway-test results on various surfaces.

Vehicle Speed (miles/h)	Transient Time (ms)			BFC		Distance (ft)		
	τ_1	τ_2	τ_3	F_1	F_3	d_1	d_2	d_3
Test C2								
30	7.8	19.5	82.0	53.8	33.8	0.34	0.86	3.61
40	9.8	17.6	39.0	42.5	25.0	0.57	1.03	2.29
50	8.8	18.6	66.4	42.5	17.5	0.64	1.36	4.87
Avg	8.8	18.6	62.5					
Test C3								
31	13.7	23.4	82.0	56.3	36.3	0.62	1.06	3.73
39	11.7	21.5	46.9	57.5	25.0	0.67	1.23	2.68
50	7.8	15.6	25.4	50.0	20.0	0.57	1.14	1.88
Avg	11.1	20.2	51.4					
Test C5								
30	11.7	22.5	70.3	44.0	32.0	0.51	0.99	3.09
50	13.7	18.6	30.3	44.0	16.0	1.00	1.36	2.22
Avg	12.7	20.6	50.3					
Test D1								
34	11.7	17.6	25.4	50.0	22.5	0.58	0.88	1.27
44	15.6	23.4	27.3	42.5	15.0	1.01	1.51	1.76
51	13.7	19.5	25.4	40.0	7.5	1.02	1.46	1.90
Avg	13.7	20.2	26.0					
Test D2								
29	10.7	18.6	21.6	47.5	30.0	0.46	0.79	0.92
35	12.7	18.6	21.5	41.3	18.8	0.65	0.95	1.10
40	13.7	19.5	27.0	35.0	11.3	0.80	1.14	1.58
45	18.6	21.5	26.4	35.0	7.5	1.23	1.42	1.74
50	9.8	15.6	21.5	38.8	6.3	0.72	1.14	1.58
58	11.7	17.6	23.4	35.0	2.5	1.00	1.50	1.99
Avg	12.9	18.6	23.6					
Test D3								
32	7.8	14.6	21.5	42.5	20.0	0.37	0.69	1.01
32	11.7	19.5	23.4	47.5	20.0	0.55	0.92	1.10
35	11.7	18.6	23.4	43.1	15.0	0.60	0.95	1.20
35	11.7	17.6	23.4	42.5	17.5	0.60	0.90	1.20
42	9.8	15.6	20.5	42.5	7.5	0.60	0.96	1.26
Avg	10.5	17.2	22.6					
Test D4								
32	15.6	23.4	30.0	52.5	17.5	0.73	1.10	1.41
35	20.5	20.5	20.5	55.0	11.3	1.05	1.05	1.05
40	15.8	19.5	27.3	57.5	7.5	0.93	1.14	1.60
45	11.7	15.8	21.5	47.5	7.5	0.77	1.04	1.42
52	9.8	17.6	23.4	37.5	6.3	0.75	1.34	1.78
59	5.9	13.7	19.5	31.3	1.3	1.51	1.19	1.69
Avg	13.2	18.4	23.7					
Test D5								
32	13.7	19.5	23.4	40.0	15.0	0.64	0.92	1.10
36	18.5	18.5	18.5	38.8	7.5	0.98	0.98	0.98
41	23.4	23.4	23.4	35.0	7.5	1.41	1.41	1.41
46	9.8	15.7	23.4	35.0	5.0	0.66	1.06	1.58
51	9.5	19.5	25.4	35.0	3.8	0.71	1.48	1.90
58	7.8	17.6	23.1	32.5	2.5	0.67	1.50	1.97
Avg	13.8	19.0	22.9					
Test D6								
32	13.7	17.6	21.5	45.0	17.5	0.64	0.83	1.01
35	15.9	20.1	25.6	41.3	7.5	0.82	1.03	1.31
40	7.8	15.6	19.5	37.5	8.8	0.46	0.92	1.14
46	7.8	13.7	21.5	32.5	6.3	0.53	0.92	1.45
51	11.9	18.6	27.3	32.5	5.0	0.89	1.39	2.04
Avg	11.4	17.1	23.0					
Test D7								
36	9.8	17.6	21.5	32.5	15.0	0.52	0.93	1.14
Test D8								
35	12.7	16.6	29.3	50.0	18.8	0.65	0.85	1.50
40	24.4	29.3	32.1	45.0	12.5	1.43	1.72	1.88
45	11.7	18.6	23.4	42.5	10.0	0.77	1.23	1.54
51	7.8	15.3	21.5	52.5	10.0	0.58	1.14	1.61
57	9.8	18.6	25.4	40.0	5.0	0.82	1.55	2.12
Avg	13.3	19.7	26.3					
Test D9								
35	8.8	15.6	21.5	70.0	25.0	0.45	0.80	1.10
35	5.9	15.0	21.5	70.0	25.0	0.30	0.77	1.10
36	7.8	13.7	19.5	58.0	20.0	0.41	0.72	1.03
Avg	7.5	14.8	20.8					
Test D10								
38	10.7	15.6	19.5	51.3	20.0	0.60	0.87	1.09
40	9.8	13.7	21.5	44.4	16.3	0.57	0.80	1.26
45	22.5	27.3	31.3	46.3	11.3	1.49	1.80	2.07
50	13.7	18.6	22.5	35.0	8.8	1.00	1.36	1.65
55	10.7	19.5	25.4	37.5	5.0	0.86	1.57	2.05
Avg	13.5	18.9	24.0					
Test J1								
29	21.5	27.3	32.2	37.5	20.0	0.91	1.37	1.16
33	17.6	25.4	33.2	33.8	12.5	0.85	1.61	1.23
39	25.4	28.3	31.3	30.0	10.0	1.45	1.80	1.62
39	13.7	19.5	25.4	22.5	10.0	0.78	1.45	1.29
44	20.5	23.4	33.2	22.5	7.5	1.32	2.14	1.45
Avg	19.75	24.8	31.06					
Test J2								
29	19.5	19.5	32.2	38.1	15.6	0.83	1.37	0.83
29	17.6	27.3	36.1	35.0	16.3	0.75	1.53	1.16
34	13.7	20.5	29.3	35.0	13.8	0.68	1.46	1.02
39	13.7	17.6	25.4	28.8	8.8	0.78	1.45	1.01
45	13.7	19.5	37.1	30.0	7.5	0.90	2.45	1.29
Avg	15.6	20.9	32.0					
Test J3								
28	13.7	15.6	35.2	32.5	20.0	0.56	1.45	0.64
14	15.6	24.4	39.1	21.3	12.5	0.78	1.95	1.22
45	11.7	19.5	30.3	27.5	8.9	0.77	2.00	1.29
49	9.7	13.7	33.2	25.0	10.0	0.70	2.39	0.98
Avg	12.7	34.5	18.3					
Test J4								
30	11.7	15.6	21.5	35.0	20.0	0.95	0.51	0.69
40	15.6	23.4	35.1	25.0	7.5	0.91	1.37	2.06
45	15.6	23.4	39.0	39.0	7.5	1.03	1.54	2.57
Avg	14.3	20.8	31.9					
Test J6								
29	19.5	25.4	33.2	45.0	10.0	0.83	1.08	1.41
40	11.7	21.5	27.3	27.5	5.0	0.69	1.26	1.60
49	10.7	18.6	25.4	30.0	0.0	0.77	1.34	1.82
Avg	14.0	21.8	28.6					
Test J7								
29	15.6	25.4	33.2	30.0	7.5	0.66	1.08	1.41
39	15.6	19.5	29.3	17.5	3.8	0.89	1.11	1.68
45	11.7	15.6	25.4	27.5	2.5	0.77	1.03	1.68
40	9.8	17.6	27.3	27.3	2.5	0.72	1.29	2.00
34	15.6	20.5	31.3	23.8	6.3	0.78	1.02	1.56
Avg	13.7	19.7	29.3					
Test J8								
27	14.6	22.5	34.2	27.5	16.3	0.58	0.89	1.35
39	13.7	19.5	33.2	30.0	10.0	0.78	1.11	1.9
Avg	14.2	21.0	33.7					

Table 5 continued.

Vehicle Speed (miles/h)	Transient Time (ms) τ_1	τ_2	τ_3	BFC F_1	F_3	Distance (ft) d_1	d_2	d_3
Test J9								
32	11.7	18.6	34.2	42.5	13.8	0.55	0.87	1.60
40	13.7	24.4	29.3	35.0	8.9	0.80	1.43	1.71
44	7.8	15.6	26.4	36.9	8.9	0.50	1.00	1.70
49	5.8	13.8	25.4	35.0	7.5	0.42	0.99	1.82
Avg	9.8	18.1	28.8					
Test J10								
29	7.8	10.7	23.4	42.5	20.6	0.33	0.45	0.98
39	9.8	23.4	31.3	40.0	15.0	0.56	1.34	1.79
Avg	8.8	17.0	27.4					
Test J11								
29	7.8	19.5	31.3	27.5	12.5	0.33	0.83	1.33
39	13.7	–	31.5	23.8	7.5	0.78	–	1.80
44	8.8	19.5	31.1	17.5	3.8	1.57	1.26	2.01
49	11.7	–	31.3	17.5	1.3	0.84	–	2.25
Avg	10.5	19.5	31.3					
Test J12								
28	13.7	19.5	31.3	35.0	13.8	0.56	0.80	1.29
39	7.8	19.5	39.1	22.5	7.5	0.45	1.12	2.24
44	11.7	21.5	31.3	22.5	5.0	0.76	1.39	2.02
Avg	11.1	20.2	33.9					
Test J16								
39	7.8	19.5	27.3	16.0	8.0	0.45	1.12	1.56
44	11.5	23.4	35.2	–	5.0	0.74	1.51	2.27
49	17.6	29.3	35.1	14.0	4.0	1.26	2.11	2.53
54	17.6	26.4	33.2	18.0	2.0	1.39	2.09	2.63
Avg	13.6	24.7	32.6					
Test J17								
30	12.7	19.8	27.3	25.0	12.5	0.56	0.87	1.20
40	13.7	21.5	27.3	22.5	10.0	0.80	1.26	1.60
45	7.8	15.6	29.3	22.5	10.6	0.51	1.03	1.93
Avg	11.1	19.0	28.0					
Test J18								
33	19.5	25.4	31.2	31.3	12.3	0.94	1.23	1.51
36	11.7	18.6	27.3	30.0	10.0	0.62	0.98	1.44
41	14.6	18.6	23.5	30.0	8.3	0.88	1.12	1.41
46	11.9	17.6	26.4	22.5	5.8	0.80	1.19	1.78
52	10.7	18.6	27.3	–	7.5	0.82	1.42	2.08
Avg	13.5	19.8	27.1					
Test J19								
30	13.7	17.6	27.3	25.0	3.8	0.60	0.77	1.20
35	8.8	13.7	23.4	21.3	8.8	0.45	0.70	1.20
41	7.8	17.6	25.4	25.0	10.0	0.47	1.06	1.53
46	11.7	13.8	23.4	21.3	6.3	0.79	0.93	1.58
51	7.8	14.6	22.5	20.0	5.0	0.58	1.09	1.68
Avg	13.7	17.5	24.4					

Note: 1 mile/h = 1.6 km/h; 1 ft = 0.33 m.

Table 6. Summary of highway-test results.

Categories Compared	Transient Time (ms) τ_1	τ_2	τ_3
C2	8.8	18.6	62.5
C3	11.1	20.4	51.4
C5	12.7	20.6	50.3
Avg	10.9	19.9	54.7
D1	13.7	20.2	26.0
D2	12.9	18.6	23.6
D3	10.5	17.2	22.6
D4	13.2	18.4	23.7
D5	13.8	19.0	22.9
D6	11.4	17.1	23.0
D8	13.3	19.7	26.3
D10	13.5	18.9	24.0
Avg	12.8	18.6	24.0
J1	19.8	24.8	31.1
J2	15.6	20.9	32.0
J3	12.7	18.3	34.5
J4	14.3	20.8	31.9
J6	14.0	21.9	28.6
J7	13.7	19.7	29.3
J8	14.2	21.0	33.7
J9	9.8	18.1	28.8
J10	8.8	17.0	27.4
J11	10.5	19.5	31.3
J12	11.1	20.2	33.9
J16	13.6	24.7	32.6
J17	11.1	19.0	28.0
J18	13.5	19.8	27.1
J19	10.0	17.5	24.4
Avg	12.8	18.7	30.2
D	12.8	18.6	24.0
C	10.9	19.9	54.7
J	12.8	18.7	30.2
Avg	12.2	19.0	36.3

tire vertical load is found to be insignificant on the duration of τ_1, τ_2, or τ_3 (Table 6) for each of the three surfaces. In fact, the average transient-time duration τ_1 or τ_2 for the three test series is approximately the same, which suggests that the effect of texture is also insignificant on the transient-time duration. Thus it can be concluded that the transient-time durations are independent of the changes in the operating parameters. Similar conclusions were also drawn from the laboratory tests on the fine-textured belt. As in the laboratory tests, the final BFC values (steady-state BFC) decrease with increasing speed. This trend, which has been well documented (6,8), supports the experimental procedure and also, in turn, supports the validity of the laboratory tests. It may be recalled that similar trends were noted in the laboratory test results also.

COMPARISON OF LABORATORY AND HIGHWAY TEST RESULTS

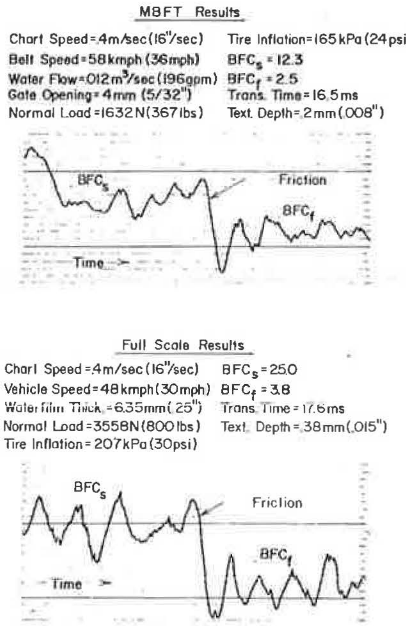
Figure 8 shows a comparison of typical friction-time traces from the laboratory tests and the highway tests. Although the test conditions are different, the traces are similar in qualitative shape. Moreover, the transient-time durations under these different operating conditions are also similar (16.5 ms in the laboratory versus 17.6 ms on the highway).

The similarity between the highway tests and the laboratory tests establishes the following facts:

1. The laboratory test results represent realistic highway situations as far as the character of the transient time from the nonhydroplaning state to the hydroplaning state is concerned and
2. The character of the transient time is unaffected by operating parameters (speed, film thickness, inflation pressure, or texture).

The duration of the transient condition during which the available friction value decreases varies between 7 and 65 ms under a broad spectrum of operating conditions. For practical purposes, this response-time range is instantaneous when compared with other response times in the complete system of vehicle and driver. Driver response is of the order of 1-2 s and the vehicle-response times are of the

Figure 8. Comparison of laboratory test on textured belt with highway test on Jennite.



order of 1-1.5 s. These are an order of magnitude greater than the tire-response times found in this study. The significance of this finding is that, for a simulation of a vehicle, the tire characteristics can be considered instantaneous when conditions such as the water-film thickness change instantly.

CONCLUSIONS

The following conclusions are drawn from the results of this research:

1. When a moving tire encounters a sudden increase in the water layer in its path, up to 65 ms are required for the friction force to drop from a nonhydroplaning condition to a hydroplaning condition in the region of the thick water layer. Speeds during this transitory period range from 48 to 96 km/h (30-60 miles/h).
2. The laboratory and the highway tests show that, in the range of operating variables considered, the transient times do not vary significantly. These times can be considered instantaneous when compared with the complete system of vehicle and driver. Thus highway-maintenance requirements are dictated by the vehicle response to these transient inputs.
3. The friction force goes through a minimum value before reaching the steady state. However, the time during which the friction force is below the steady-state value is very short.

It is suggested that further study of tire hydroplaning during sudden changes in the water layer in the path of the tire would be worthwhile. Specifically, the following recommendations are made:

1. Since the mechanics of tire-contact-area deformation are different for a radial tire than for bias and belted tires, transient and steady-state hydroplaning characteristics of radial tires should be investigated.
2. The effect of the transitory period on the vehicle dynamics characteristics should be studied. This may clarify some of the problems associated with differential braking of vehicles that result in loss of directional control.

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