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16. Abstract
Findings concerning snubbing (pulsing) versus dragging strategies for braking trucks and buses to control speeds on downgrades are presented in this report. Vehicle tests were performed on a long steep grade (approximately six or seven percent for five miles). A mobile dynamometer was used to study individual brakes. A simplified heat flow model was used in planning the experiments and analyzing the results.

The basic findings are: (1) the average temperature per pound of brake drum is practically equivalent whether light dragging or snubbing is used to control speed; (2) the hottest brakes will be cooler if snubbing is used; and (3) on short downhill descents, the dragging strategy will cause hot spots to develop to a greater extent.

Recommendations concerning the wording of manuals used for commercial driver license (CDL) training are given.

17. Key Words
Downhill braking, control speeds on downgrades, truck brake temperatures, truck runaway

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THE INFLUENCE OF BRAKING STRATEGY ON BRAKE TEMPERATURES IN MOUNTAIN DESCENTS

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1.0 INTRODUCTORY SUMMARY

This report presents findings concerning snubbing and dragging strategies for braking heavy vehicles (trucks and buses) to control speed on downgrades.

For many years, there has been controversy between those who recommend dragging the brakes and those who recommend snubbing (pulsing) to control speed. Recently, interest in commercial driver license (CDL) training has stimulated discussions of the merits of these two braking strategies. Specifically, the CDL manual [1] favors the dragging technique and states that the on-and-off method builds up more heat than a light, steady braking method does.

However, experimental evidence supporting or refuting this position has not been generally available. Furthermore, theoretical considerations indicate that either method should result in nearly the same average temperature across all brakes as long as the same average speed is maintained. Consequently, to aid the Federal Highway Administration (FHWA) in advising the commercial vehicle community on downhill braking strategy, the University of Michigan Transportation Research Institute (UMTRI), with cooperation from the National Highway Traffic Safety Administration (NHTSA), performed the tests and experiments described in this report from UMTRI.

The basic findings of these tests and experiments involving heavy vehicles with air-actuated brakes are as follows:

- The average temperature per 100 lb of brake drum is practically equivalent whether the light dragging or the snubbing strategy is used for controlling the speed of heavy trucks on long steep downgrades. (Mobile dynamometer experiments show that snubbing results in slightly lower temperatures than dragging but the difference is not large.)
- The hottest brake will be cooler if the snubbing strategy is used. (Even though the average temperature is approximately the same, the snubbing strategy provides for a more even utilization of all brakes compared with that attained by the light pressure involved in dragging.)
- On short (approximately one minute) downhill descents, the dragging strategy will result in a higher level of martensite formation than that formed by a snubbing strategy. (The formation of martensite can lead to drum fragmenting and it is a problem involving new brakes or recently relined brakes.)

Based on these findings, an important recommendation of this study concerns the wording used in manuals for commercial vehicle driver licensing. The following wording is suggested as a possibility for consideration in rewording CDL manuals:

"The right way to go down long grades is to use a low gear and go slow. Use close to rated engine speed to maximize drag. If you go slowly enough, the brakes will be able to get rid of enough heat so they will work as they should. The driver's most important consideration is to pick a control speed that is not too fast for the weight of the vehicle, the length of the grade, and the steepness of the grade.

Drivers who are unfamiliar with routes in mountainous regions need to select a low speed to be safe. Ideally, the driver should be familiar with the route and should be prepared by knowing the appropriate speed of descent for the vehicle as loaded. However, if the driver is not familiar with which grades are long ones, the driver needs to proceed with caution—perhaps at a low speed of no more than 20 mph on long grades.

If at all possible, the driver should plan ahead and obtain information on any severe grades. Often severe grades are well marked ahead of time by highway signs, and the driver of a heavily-laden vehicle needs to heed these warnings because overheated brakes will result from travelling too fast for the severity of the mountain and the condition of the vehicle and its braking system.

To control speed going down a mountain, some people favor using a light, steady pressure to drag the brakes while others favor a series of snubs, each sufficient to slow the vehicle by approximately 6 mph in about 3 sec. The snubbing strategy uses pressures over 20 psi for heavy trucks while the light drag may involve pressures under 10 psi. Tests have shown that either method will result in approximately the same average brake temperature at the bottom of the mountain as long as the same average speed is maintained. However, the snubbing method, due to the higher pressure involved, will aid in making each brake do its fair share of the work. Hence, the snubbing method will result in more uniform temperatures from brake to brake and thereby aid in preventing brakes from overheating.

Furthermore, light, steady pressure at highway speeds on short grades of roughly one mi in length can lead to problems with "hot spotting" and drum cracking and fragmenting if the brake linings are new.

In summary, the most important considerations are to go slow enough and use the right gear. Remember that compared to a strategy based upon a light pressure dragging, the snubbing strategy will aid in making each brake do its fair share of the work and reduce the tendency for hot-spotting and drum-cracking of new or recently relined brakes."

2.0 BACKGROUND INFORMATION CONCERNING PROJECT PLANNING, TEST PREPARATIONS, AND TESTING

Project plans called for completing the following activities:

(1) arranging for a test site, vehicles, and drivers
(2) planning and evaluating braking strategies
(3) preparing the vehicles
(4) evaluating the pertinent mechanical properties of the vehicles
(5) conducting the tests
(6) analyzing the results and
(7) reporting the findings

This section presents selected highlights of these activities as needed to provide background information for helping to understand the vehicle and brake testing results presented in later sections of this report.

2.1 Test Site, Vehicles, and Drivers

The vehicle tests were performed on I-64 going east from Beckley, West Virginia between the Bragg and Sandstone interchanges. The elevation profile of the mountain is presented in Figure 1. The slope is very important in determining the retarding power needed to control speed at a preselected value. The power required is equal to the product of the slope times the velocity times the weight of the vehicle. Examination of Figure 1 indicates that the slope is 7 percent, then 6 percent, then 7 percent, then 6.2 percent, then 4.5 percent. These variations in grade are enough to cause the brake temperatures to change at noticeably different rates on different parts of the mountain.

The UMTRI truck utilized six brakes on three axles. The front brakes were 15x4 S-cam brakes and the rear brakes were 16.5x7 S-cam brakes. The vehicle weighed 46,420 lb. Based upon analyses and preliminary runs down the mountain, a speed of 35 or 36 mph was selected as the control speed for these tests.

The brake drums used on the front axle weighed 67 lb and those on the tandem rear axles weighed 97 lb a piece. As will be shown by the downhill test results, the temperature balance of the brakes on this vehicle is very good and each brake is doing its "fair share" of the work.

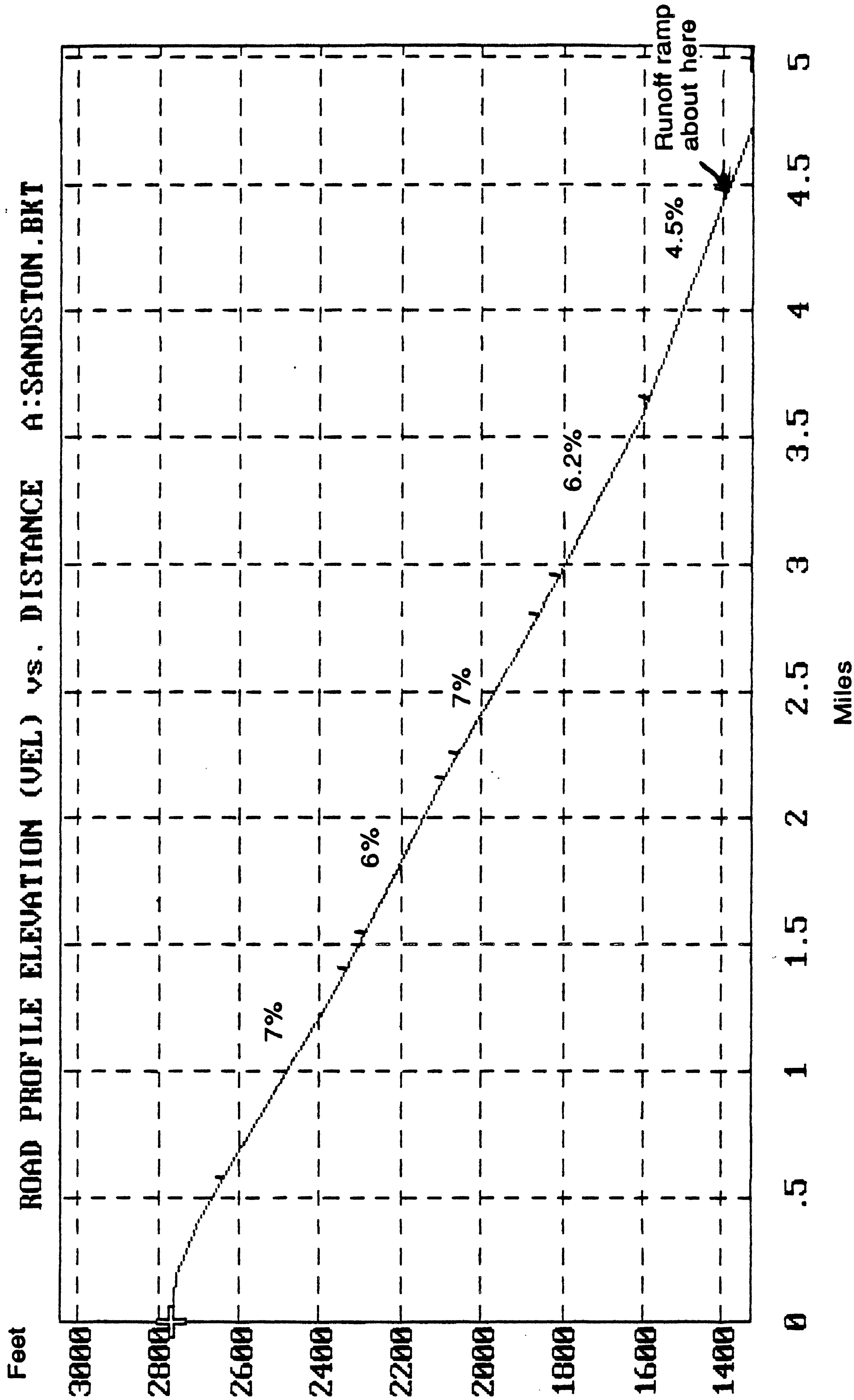


Figure 1. Road Profile Elevation v. Distance

Based upon preliminary testing of the vehicle, the cooling coefficient for a rear brake on the UMTRI truck was 0.035 hp/°F at 35 mph, or in other units approximately, 20 ft lb/sec°F. This means that a rear brake will cool at a rate of about 0.4°F/sec when the brake temperature is about 300° F above ambient temperature. Very roughly, a rear brake drum may take 20 min to cool from 600° F to 200° F with the vehicle travelling at 50 mph. Small differences in cooling rate (as might be brought about by pulsing versus dragging brakes, for example) will not have a large influence upon the maximum temperatures attained—perhaps 30° F is possible, but that is not much for experiments of this type involving a component as variable as truck brakes.

The NHTSA vehicle was a tractor semitrailer (3-S2) with characteristics that differed from those of the UMTRI truck. The tractor semitrailer weighed nearly 80,000 lb. It used ten brakes. It was tested in three states of pneumatic balance (A, B, and C) as indicated in Table 1. An important difference between the two vehicles was that the NHTSA vehicle did not have a uniform temperature balance in any of its three states of balance. The trailer brakes did much more work than the brakes on the tractor's drive axles. This was due to the pneumatic balance tending to keep the brakes on the drive axles at lower pressures and because the trailer brakes were more effective than the drive axle brakes. In addition, the cooling rates of the brakes and the natural retardation were less for the NHTSA vehicle than for the UMTRI truck. As will be seen, the characteristics of the NHTSA vehicle led to very high temperatures on the trailer brakes. In an attempt to control the maximum brake temperature, the NHTSA vehicle was driven down the mountain at 25 mph at first and then at 20 mph later. (Some runs were aborted when the temperature of the hottest brake reached approximately 1000° F.)

Table 1. Downhill Braking Tests. Average Threshold Pressures per SAE Practice J1505

State	Front	Drive	Trailer
A	6.4	8.4	6.9
B	10.0	12.1	6.9
C	10.0	8.4	6.9

Drivers who were experienced in conducting vehicle tests were used and they followed well-defined braking strategies for controlling speed during the mountain descents. The drivers did not pick the braking strategy. They followed directions (a) to maintain a constant control speed using a light pressure or (b) to make snubs from 3 mph above a selected control speed to bring vehicle speed to 3 mph below the selected control speed, then allowing the vehicle to coast up to 3 mph above the control speed before applying the brakes again.

2.2 Planning and Evaluating Braking Strategies

In addition to full scale vehicle tests, simulations were used to investigate braking strategies and special experiments were performed with the UMTRI Mobile Dynamometer. The simulation provides the capability for studying the sensitivity of brake temperatures to changes in the vehicle, its braking system, or the braking strategy used. The mobile dynamometer experiments, on the other hand, allow the examination of the performance of a single brake without interactions with other brakes in a vehicle braking system.

The mobile dynamometer was used to address three questions:

(1) Is there a difference in cooling between snubbing or dragging the brake?

(2) Is the formation of martensite and the likelihood of drum-cracking greater for dragging or snubbing?

(3) How will automatic slack adjusters perform if they are installed on vehicles using a snubbing strategy?

The results of the dynamometer experiments are presented in Section 4.

The simulation model employed in this study was the UMTRI "Brake Temperature" model [2,3]. This model has the features used in the "Grade Severity Rating System," being developed by FHWA [4,5], plus the ability to treat each brake separately, thereby providing information on the hottest brake, the coolest brake, etc. and on the influences of the proportioning of braking effort and other differences from brake to brake. The knowledge represented by the concepts in the models indicate that the important factors influencing brake temperatures in mountain descents include:

(1) vehicle weight
(2) vehicle velocity
(3) slope of grade
(4) length of grade
(5) number of operational brakes
(6) proportion of the total braking effort done by each brake
(7) cooling of each brake
(8) natural retardation (aerodynamic drag and rolling resistance)
(9) engine drag
(10) retarder power (retarders are not a central subject for this study)
(11) mass of each brake

Example sets of parametric data for representing the pertinent mechanical properties of the UMTRI and NHTSA vehicles are presented in Appendix A. Example predictions of brake temperatures on the Bragg/Sandstone downgrade are also given in the Appendix A.

2.3 Vehicle Preparation

Vehicle preparations consisted primarily of (a) making sure the braking systems were functioning properly; (b) loading the vehicles to the GCW's selected for the tests; (c) providing provisions for valve changes; and (d) instrumenting the vehicles.

The brake systems were thoroughly inspected. The linings had very little wear. The brakes were adjusted. Preliminary testing of the vehicles included:

(1) brake testing, including measurements of:
- brake timing (application and release times)
- pressure balances (valve cracking and pushout pressures)
- torque balances (chassis dynamometer tests)
- stroke versus pressure without wheel rotation (and with wheel rotation)
- brake cooling rates at the control speed used in the mountain descents plus cooling rates at zero velocity

(2) vehicle coast-down tests on a level surface to obtain measurements of parasitic drag ("natural retardation" and engine drag) with the clutch (a) engaged and (b) disengaged.

(3) a stopping distance test from 45 mph on a good, level surface to demonstrate satisfactory braking capability.

The results of these tests assured that braking performance was normal and that there were not any unusual properties that would influence brake temperatures in a strange manner.

The UMTRI vehicle (see Figure 2) was loaded to 46,420 lb. to represent a heavily-loaded straight truck. The tractor was loaded at its fifth wheel by the semitrailer. However, the semitrailer's brakes were put on a separate braking circuit that was not used in downhill testing. Hence, the UMTRI vehicle was operating like a heavily-laden straight truck.

(The semitrailer's brakes were available for use as a safety measure in case the tractor's brakes faded to the point that the driver felt that the truck was starting to runaway. It turned out that the trailer's brakes were never needed in downhill testing. The semitrailer's brakes were connected to make a normal braking system for use in driving to and from the test area.)

The NHTSA vehicle was a three-axle tractor pulling a two-axle flatbed semitrailer. The vehicle was loaded to 80,000 lb using cement blocks as shown in Figure 3. The

Figure 2. UMTRI Truck on the Mountain

Figure 3. NHTSA 3-S2 Tractor-Semitrailer

tractor was equipped with a retarder for use in emergency situations. (No emergencies arose and the retarder was only applied in a few runs to check its functionality.)

Both the UMTRI and NHTSA tractors were "plumbed" so that different valves could be employed to change the brake proportioning. The UMTRI tractor had a front limiting valve that could be introduced to reduce front braking effort. The NHTSA tractor had high-flow, quick-release couplers between valves that could be used to change the braking effort as indicated in Table 1. The vehicles were instrumented to measure:

(1) lining temperatures at each brake
(2) drum temperature at each brake
(3) brake chamber pressure at each axle or axle group
(4) treadle pressure(s)
(5) velocity
(6) stroke at each brake

In addition, the NHTSA vehicle was equipped to measure stopping distance. (See Appendix B for further information on the instrumentation. See Appendix C for more information on the vehicles themselves.)

2.4 Conducting the Tests

2.4.1 Background on Downhill Testing. The vehicles were driven to the Bragg/Sandstone test site on I-64 and the instrumentation and data gathering systems were activated.

The plans for the downhill tests were based on an appreciation for the management of the energy involved in descending a mountain. The total energy absorbed by the brakes will depend upon the change in potential energy in descending the mountain. The change in potential energy is equal to the weight of the vehicle multiplied by the change in elevation which is equal to the average slope multiplied by the length of the downgrade. For example, the change in potential energy for the UMTRI truck descending the Bragg/Sandstone mountain for 4 mi is equal to 58.5 million ft lb. If all of this energy were to go uniformly into the brakes on the UMTRI truck, the change in average brake temperature would be approximately 1100° F. However, rolling resistance and engine drag might dissipate 20 to 30 million ft lb, resulting in maximum average temperature changes of approximately 700° F to 500° F. In addition, the brakes are also cooling during the descent such that in practice the maximum average temperature change turned out to be approximately 380° F at the bottom of the mountain for the UMTRI truck.

Natural retardation from the rolling resistance of the tires and other sources of rolling resistance is equal to approximately 1 to 1.5 percent of the weight. (It is like a 1 to 1.5 percent reduction in grade.) The engine provides additional retardation if the clutch is engaged. For a given speed down the hill, the driver should pick a gear that will result in an engine speed near rated speed. This will provide a much higher level of engine drag than that which would be obtained if the driver had picked a gear that resulted in a low engine speed. It is important that drivers understand that the use of a high engine speed and a low vehicle speed is the way that they can control brake temperatures. Altogether rolling resistance, engine drag, and aerodynamic drag may provide the equivalent of a 2 percent reduction in grade for speeds above 30 mph. At lower speeds, aerodynamic drag is small and the natural retardation will amount to less than 2 percent. (These numbers are approximations for new fuel-efficient vehicles and further advances in fuel economy will mean even less natural retardation.)

Given an appreciation for the need to allow enough time for the brakes to dissipate heat, the first order of business after getting the vehicle ready was to determine the proper control speed for descending the mountain. The speed needs to be slow enough for sufficient energy to flow from the brakes to keep brake temperatures from rising too much. If the vehicle is driven too rapidly, the brakes will overheat since too much energy will be stored in the brakes and not enough energy will have been dissipated from the brakes.

Preliminary runs down the mountain were made with the UMTRI vehicle at 25 mph, then 30 mph, and finally, 36 mph. Temperatures less than 600° F were achievable at 36 mph, and 36 mph was chosen as the control speed for the UMTRI vehicle.

Preliminary runs down the mountain were made at 25 mph with the NHTSA vehicle. High temperatures approaching 1000° F were recorded on some brakes and smoking was observed before the bottom of the mountain was reached. Due to the proportioning of braking effort on the NHTSA vehicle, the trailer brakes did more than their fair share of the work. The initial control speed of 25 mph was reduced to 20 mph later.

These control speeds meant that the UMTRI vehicle took approximately 400 sec in descending the mountain and the NHTSA vehicle took almost 800 sec.

After descending the mountain, the vehicles were driven several miles to the next interchange after Sandstone to provide time for the brakes to cool. By the time the UMTRI vehicle had gone to the next interchange, turned around, and climbed to the top of the mountain again, its brakes were cooled to 150° F or less. The vehicle was ready for another test. The initial brake temperatures were low enough.

Due to the high temperatures of some of the brakes of the NHTSA vehicle, further driving was often needed to reach brake temperatures less than 150° F.

Basic equations explaining the influences of vehicle speeds and time periods on brake temperatures are presented in Appendix D. The idea behind the equations is to describe the heat flow into and out of the brakes. The equations show that if the mountain is long and steep enough (that is, the potential energy change is large) and the vehicle speed is great enough, the brakes will overheat. This is because the heat flow out of the brakes (i.e., the cooling) will not have enough time to dissipate the heat absorbed by the brakes. Travelling at a lower speed will allow more time for the brakes to cool and the vehicle will reach the bottom of the mountain at lower brake temperatures.

In driving without braking, higher speed will increase the heat flow from the brakes and allow them to cool quicker. (Even though one has to drive further to lower the temperature by the same amount, it will be quicker to drive faster.)

2.4.2 Mobile Dynamometer Studies. The UMTRI mobile dynamometer was used to study a single brake. The brake was installed in the tire-wheel assembly located centrally on the test trailer of the mobile dynamometer (see Figure 4).

Instrumentation was provided in the dynamometer to measure brake torque, wheel speed, vertical load, and braking force. The brake was instrumented to measure pressure, drum and lining temperatures, and stroke (much as was done for the vehicle tests).

Figure 4. UMTRI Mobile Dynamometer

The first series of mobile dynamometer tests involved simulated mountain descents. The dynamometer was driven at 30 mph to represent a typical control speed. Snubbing and dragging strategies were used for periods of approximately 400 to 500 sec to represent long grades. The level of brake torque was controlled to simulate the amount of work done by the brake in a mountain descent. These tests were used to study the influences of braking strategies on cooling rates.

Another set of mobile dynamometer tests was used to study the influences of braking strategy on "hot-spotting" of brake drums. For these tests, the mobile dynamometer was driven at 60 mph and the brakes were applied (either snubbing or dragging) for one minute. These tests simulated speed control on mild rolling hills. Areas of hot-spotting were measured on the drums after 100 of these simulated tests, starting with green linings.

Finally, a limited study of the influence of the snubbing technique on the performance of one type of automatic slack adjuster was performed using the mobile dynamometer. The dynamometer was used to simulate mountain descents at 40 mph with a snubbing strategy consisting of cyclic applications of the brake involving 3 sec of braking at approximately 20 psi and then 6 sec off. These duty cycles of braking were continued for approximately 340 sec until the drum temperature reached approximately 600° F. Brake pressures and strokes were measured before and after four simulated mountain descents to determine if the snubbing strategy had disrupted the functioning of the automatic slack adjuster.

3.0 RESULTS FROM DOWNHILL TESTS OF COMPLETE VEHICLES

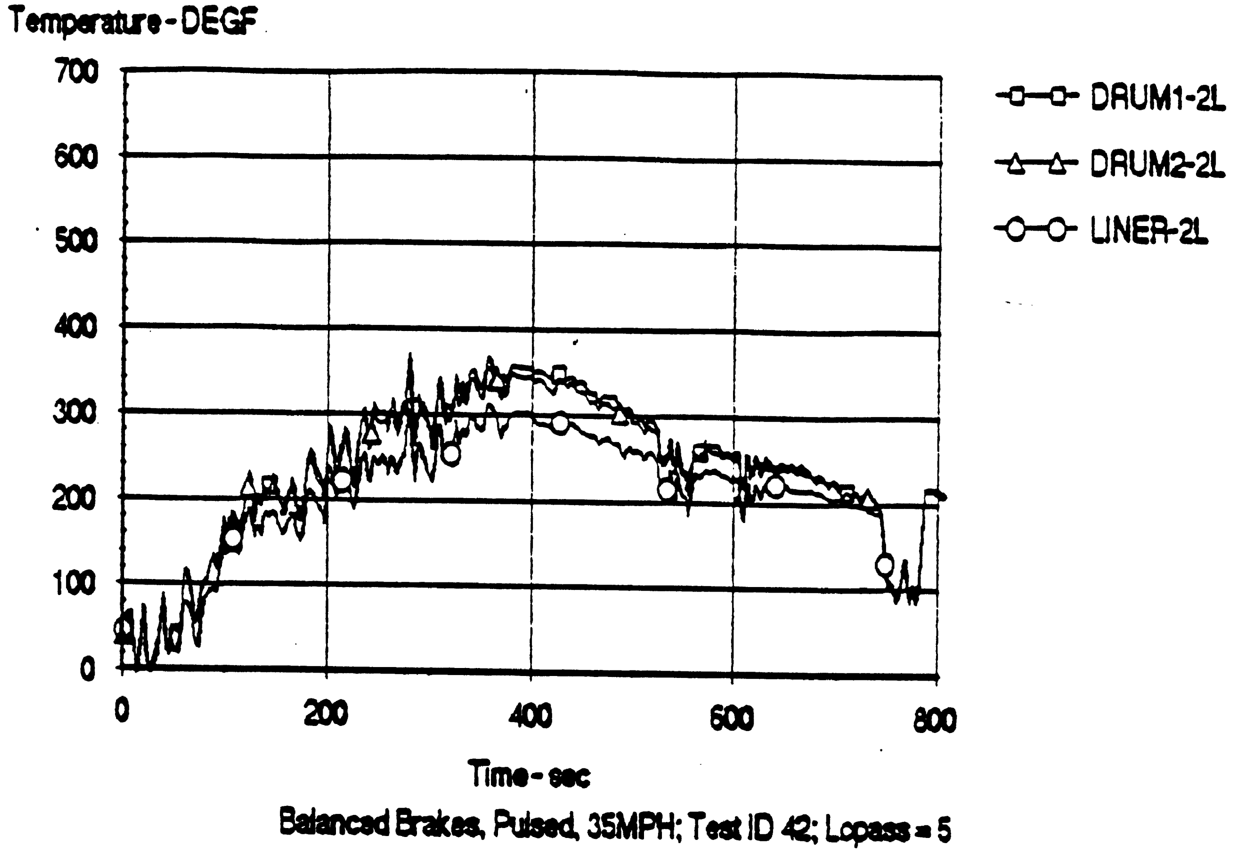
3.1 Results for the UMTRI truck.

Three temperatures were measured for each brake in the truck. (See Figure 5a for a typical example.) There were two thermocouples mounted 180° apart on the outside of the brake drum. There was another thermocouple mounted near the center of the leading shoe, per SAE procedures. The lining thermocouple readings were uniformly less than the drum thermocouple readings for all brakes and all tests. As illustrated in Figure 5a, the average of the two drum temperatures is approximately 100° F hotter than the reading from the lining thermocouple. Drum temperatures are used to present the results of this study.

The two drum thermocouples were originally intended to provide a backup in case one thermocouple failed during the testing. However, as can be seen by examining the results for the right brake on the second axle (shown at the bottom of Figure 5a), the two thermocouple readings do not necessarily agree. Further investigation has shown that this happens when the drum is not mounted exactly concentrically. The hypothesized explanation is that if the drum is not concentric, one thermocouple might be near the hot side of the drum and the other would then be near the cool side of the drum. It could also happen that even if the drum had a hot side and a cool side the thermocouples might happen to be placed so that their readings would be equal. In any event, the average of the two thermocouple readings would be a good indication of the average drum temperature. The results of these tests indicate that there is a need for two drum thermocouples to measure the average drum temperature in future test programs. The results presented for the UMTRI truck are based upon the average of the drum thermocouple readings for each brake.

The magnitude and frequency of pressure pulses and their corresponding levels of stroke for a "pulsing" (that is, a snubbing strategy) is illustrated in Figure 5b. In this case, there are some pressure pulses exceeding 20 psi and as the brake heats up, the levels of stroke exceed 1 in. At about 400 sec into the run, the hill starts to flatten out and after that only one more braking pulse is applied by the driver to control speed.

The braking strategy may be explained with reference to the velocity trace in Figure 5c. The driver holds a control speed of 36 mph ± 3 mph. When the speed reaches approximately 39 mph the driver applies a moderately aggressive brake application (around 20 psi) until the vehicle slows to 33 mph. Then the driver releases the brake allowing speed to increase to 39 mph again. The ±3 mph speed variation range quantifies the drivers control strategy for the basic pulsing technique. For this vehicle with a control speed of 35 to 36 mph on this mountain, the driver snubbed the brakes twenty-five times.



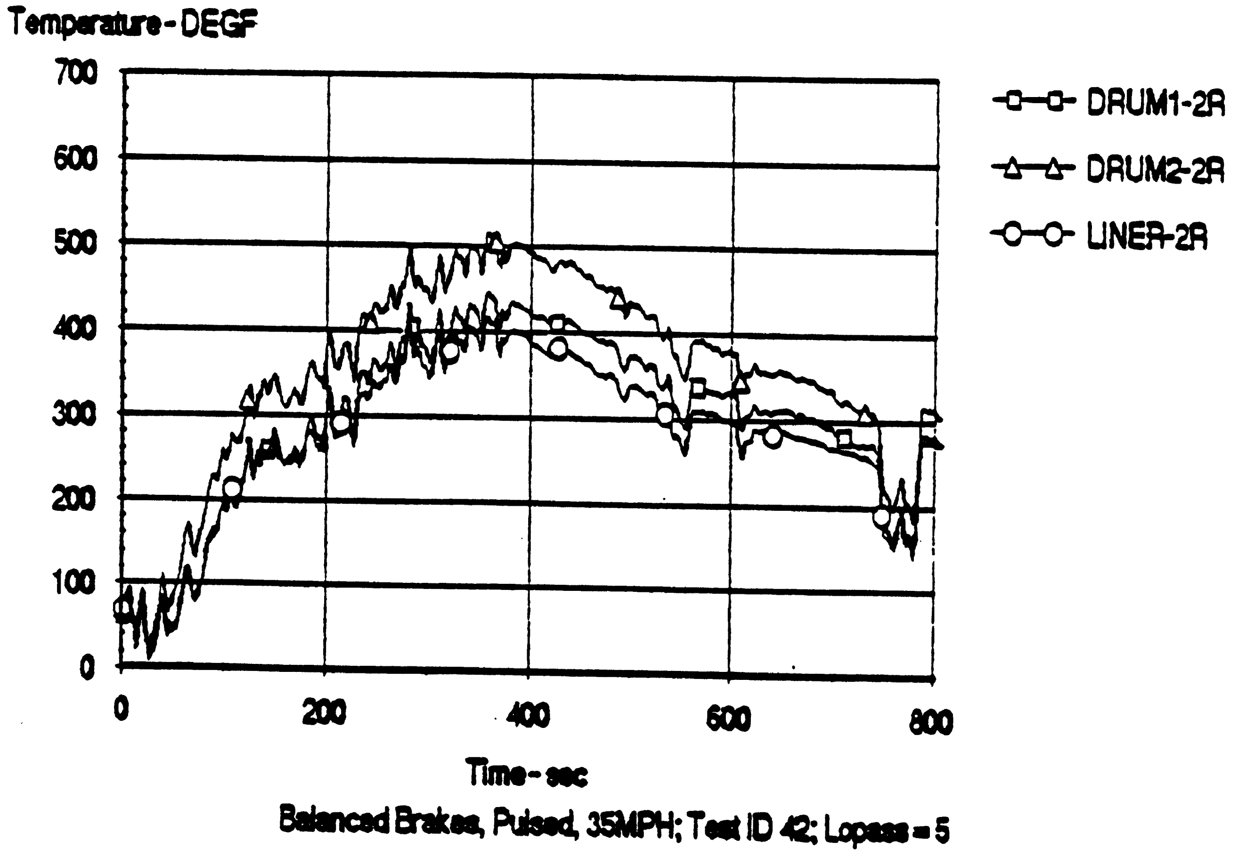
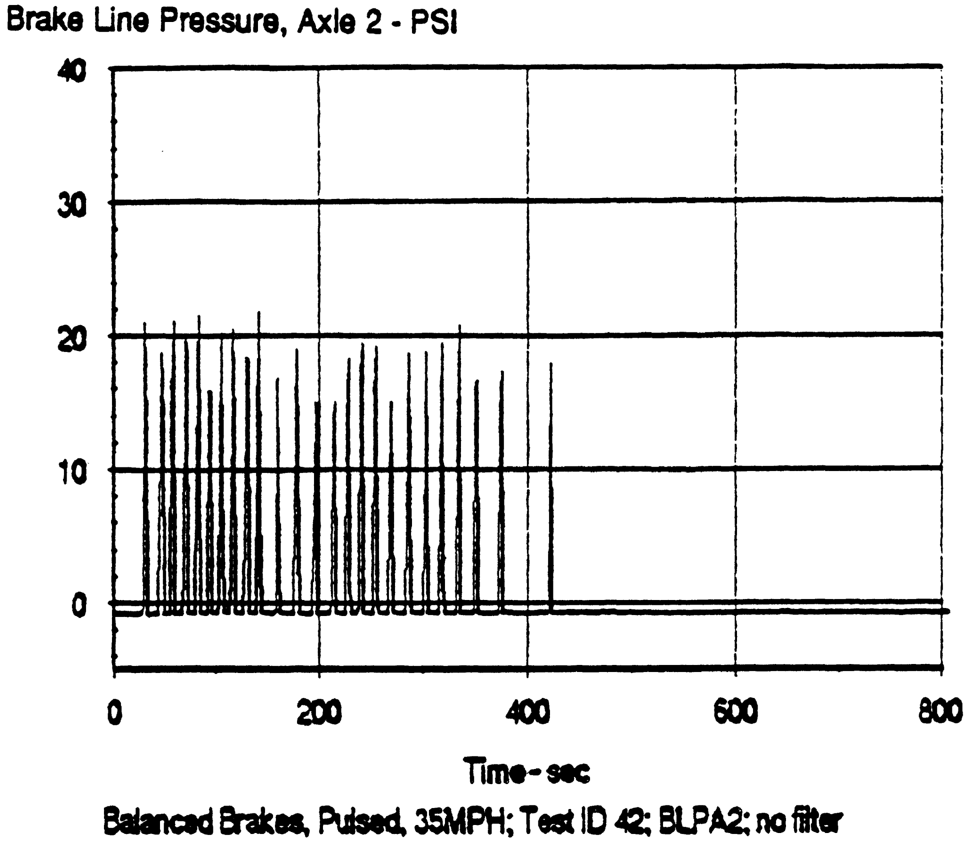


Figure 5a. UMTRI Truck Pulsing Test



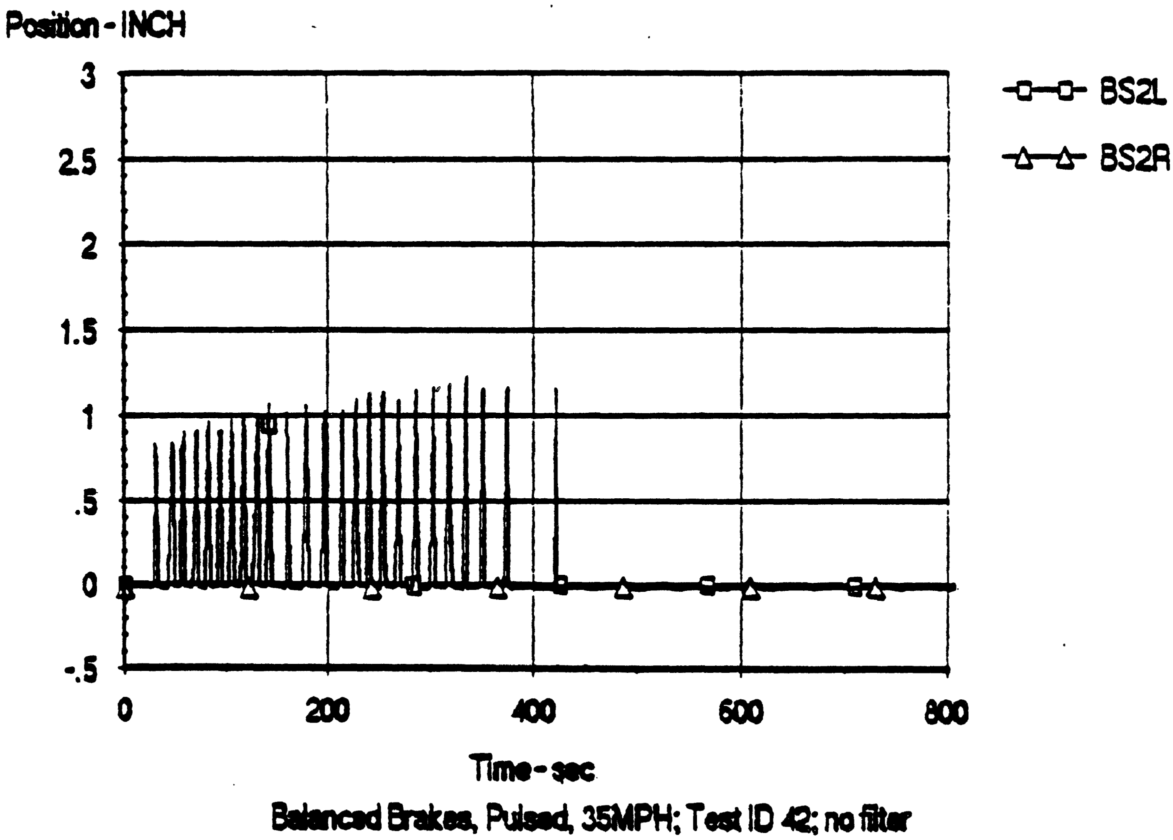
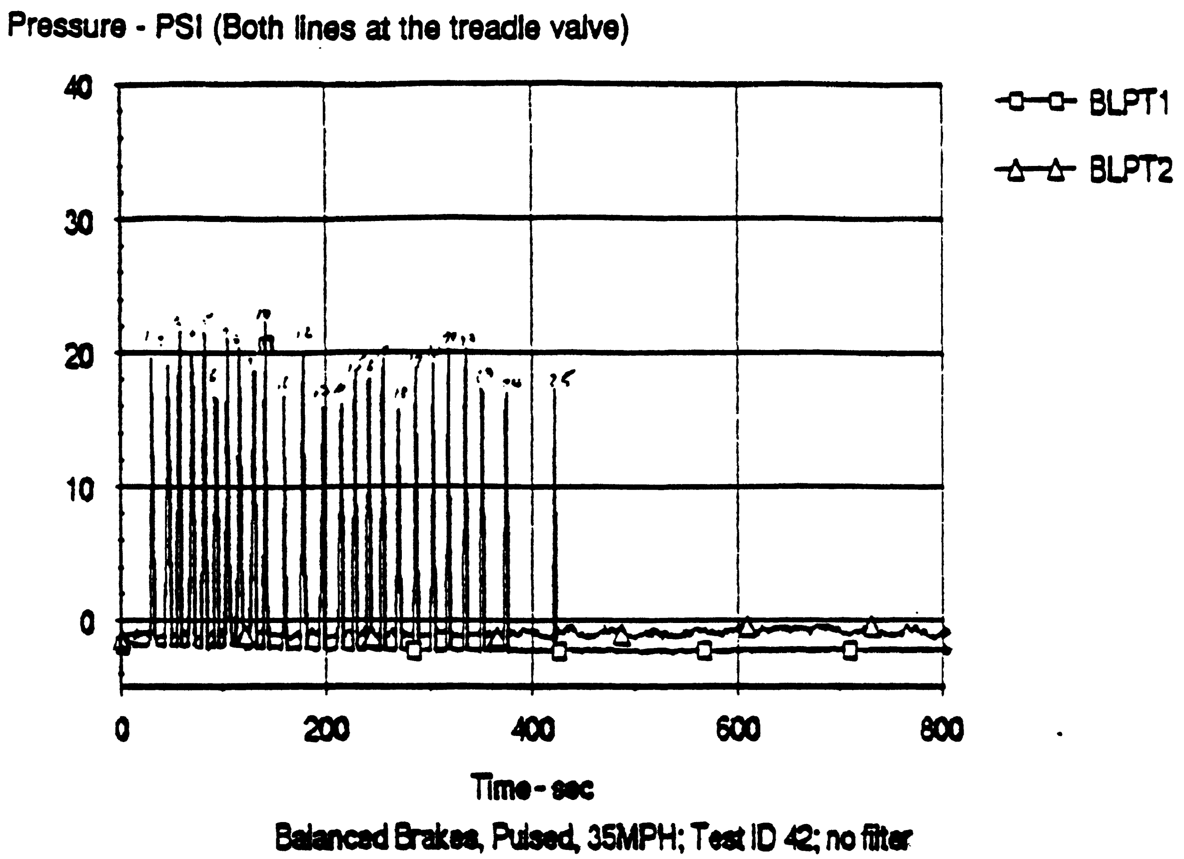


Figure 5b. UMTRI Truck Pulsing Test (continued)



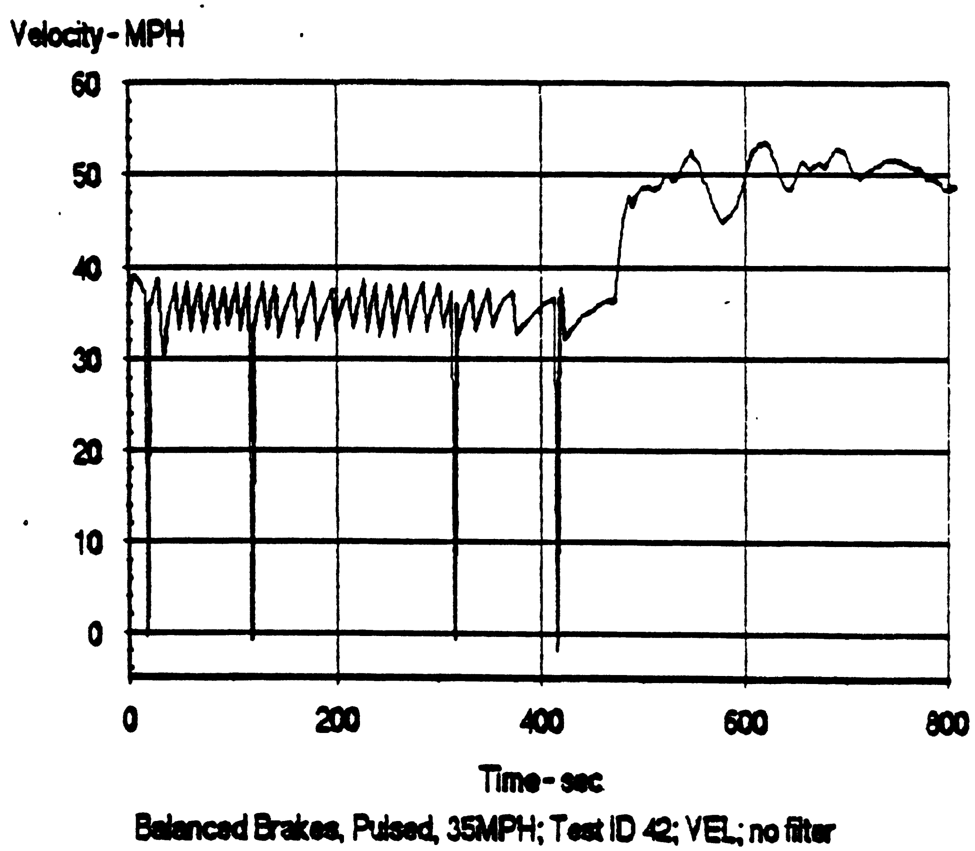


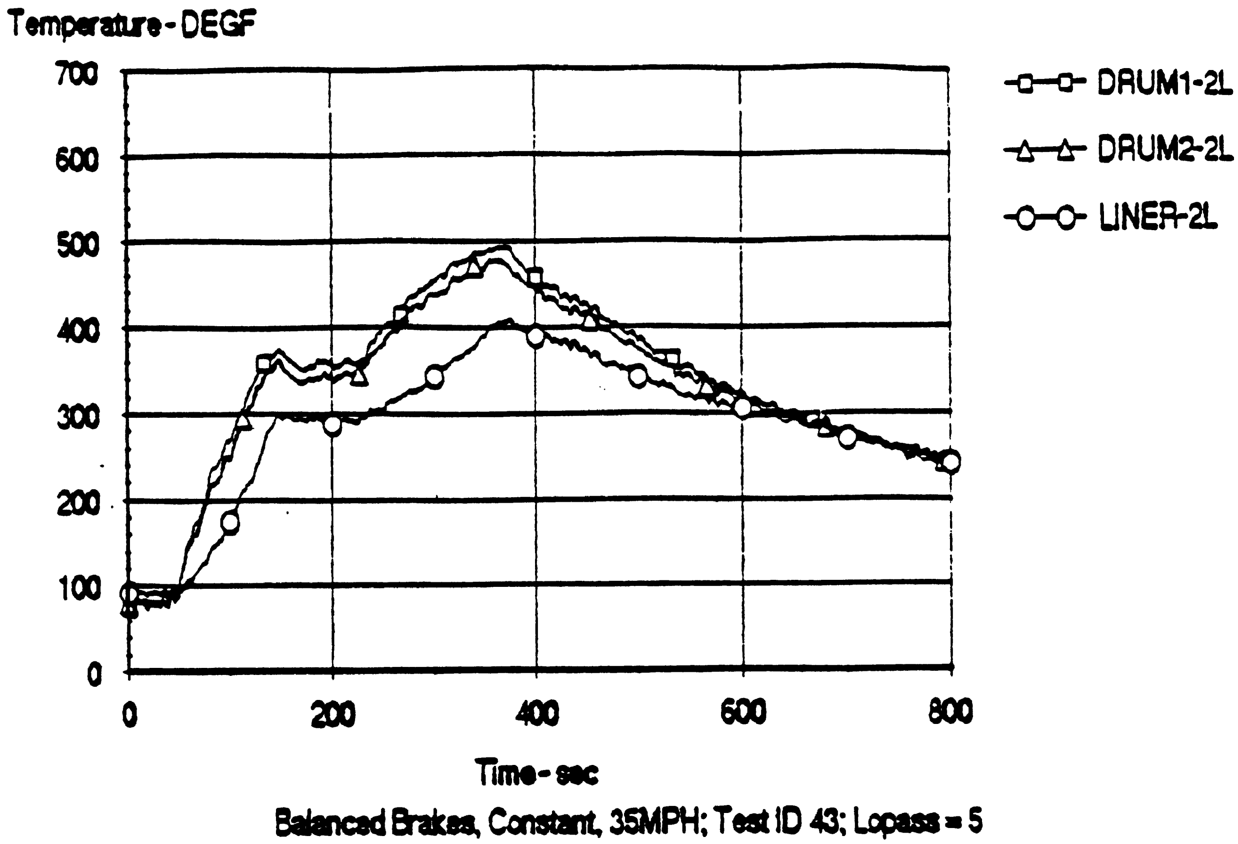
Figure 5c. UMTRI Truck Pulsing Test (continued)

Examination of the velocity trace shows large digressions to zero velocity at certain mile posts. These digressions are artificial. They are superimposed by the test operator when he noticed that the vehicle was passing a mile marker. (In this run the operator missed an intermediate mile marker.) The last marker indicated (the fifth marker on the hill) represents a point that is 4 mi down the hill from the first mile marker. This is in the vicinity of the last-run off-ramp on the mountain. It took the vehicle over 400 sec to reach this point. Note that the time between braking pulses while the vehicle is speeding up from 33 to 39 mph increases when the slope of the hill decreases—particularly between the fourth and fifth mile markers.

Figure 6 (a, b, and c) presents data comparable to that given in Figure 5 (a, b, and c) except that the driver used a so-called constant drag strategy. A better description might be a constant-velocity strategy. Examination of Figure 6c shows that the driver did a very good job of maintaining a control speed of 35 mph. However, to do this the driver needed to modulate the brakes as shown by the pressure traces presented at the tops of Figures 6b and 6c. Even though the pressure is by no means constant, it can be seen that it is generally less than 10 psi and that the corresponding stroke is well under 1 in.

Tables 2 and 3 show the results of processing the type of data illustrated in Figures 5 and 6 for run numbers ("filename") 42 and 43. The entries under "axle average" and "weighted brake-drum average" have been used to make comparisons between the influences of braking strategy, brake misadjustment, and brake balance/imbalance states. The weighted brake-drum average is computed by weighting the axle temperatures according to the relative weight of the individual brake drums. In this scheme, a front brake is given a weight of 0.67 and the other brakes are given a weight of 1.0. Then the total is divided by 5.34 to provide an equivalent average temperature for one rear brake in a perfectly balanced braking system. Given that we are going down the same mountain in nearly the same length of time, the theory here is that weighted-average brake-drum temperature will be the same for all runs (within some experimental tolerances) unless there is an appreciable difference in the cooling rates of the brakes brought about by the condition of the braking system or the braking strategy employed. In contrast, the average axle temperatures are useful for assessing the influences of braking strategy on maintaining uniform temperatures throughout all of the brakes.

The results of all of the tests performed with the UMTRI vehicle are presented in Table 4. Examination of the table indicates that the weighted average drum temperature is 32° F larger (401° versus 369° F) when the dragging strategy is used with the brakes in normal condition. This difference is not considered to be large enough to cause us to recommend one braking strategy over the other. However, this result and the results in general indicate



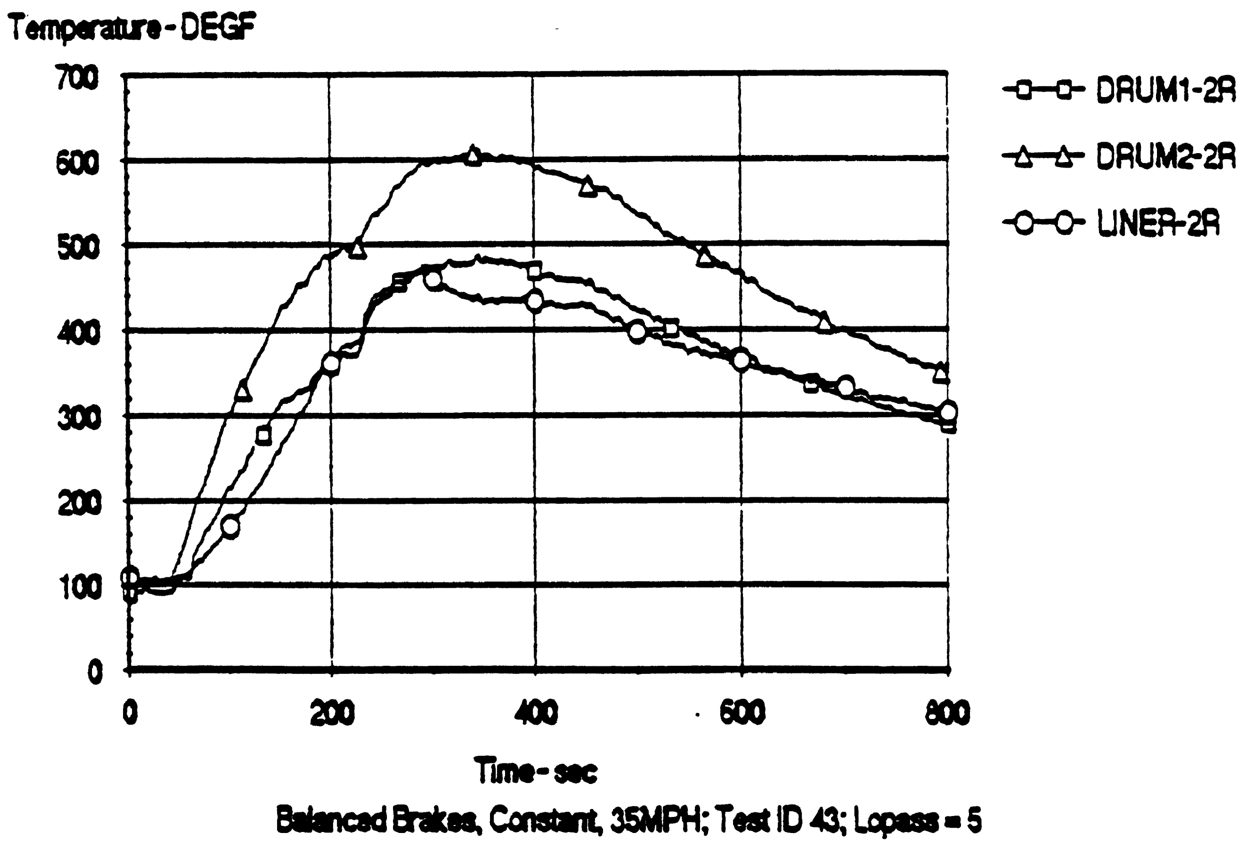
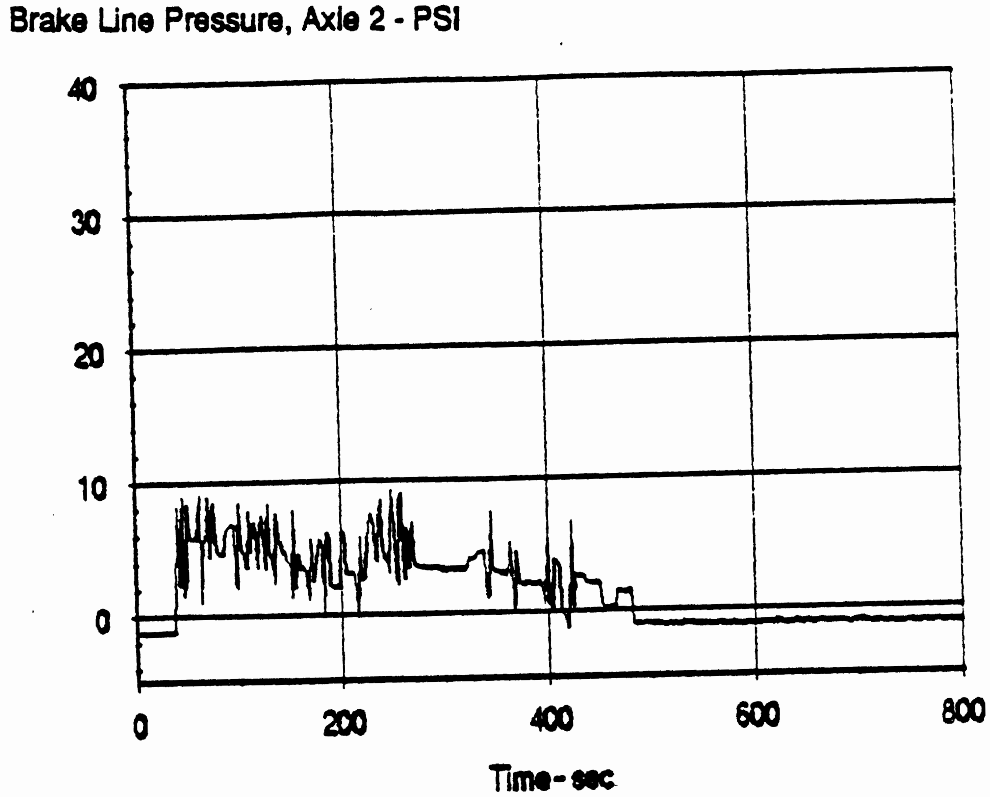
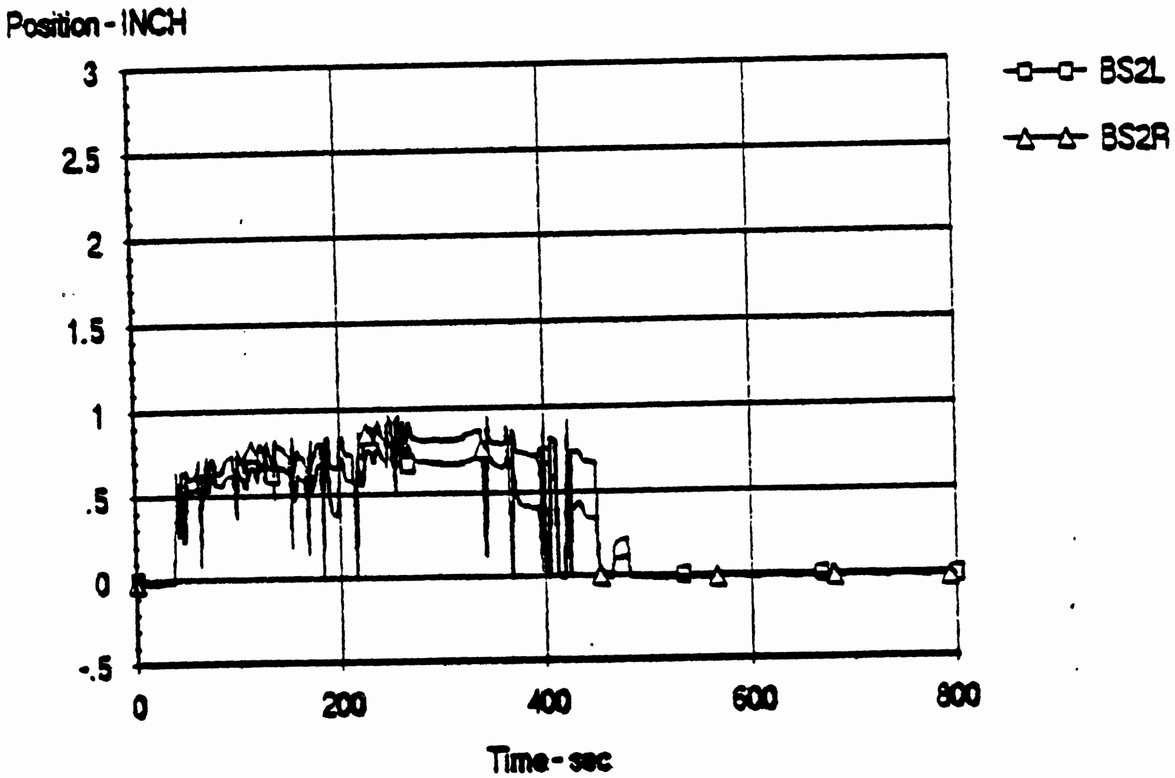


Figure 6a. UMTRI Truck Constant Drag

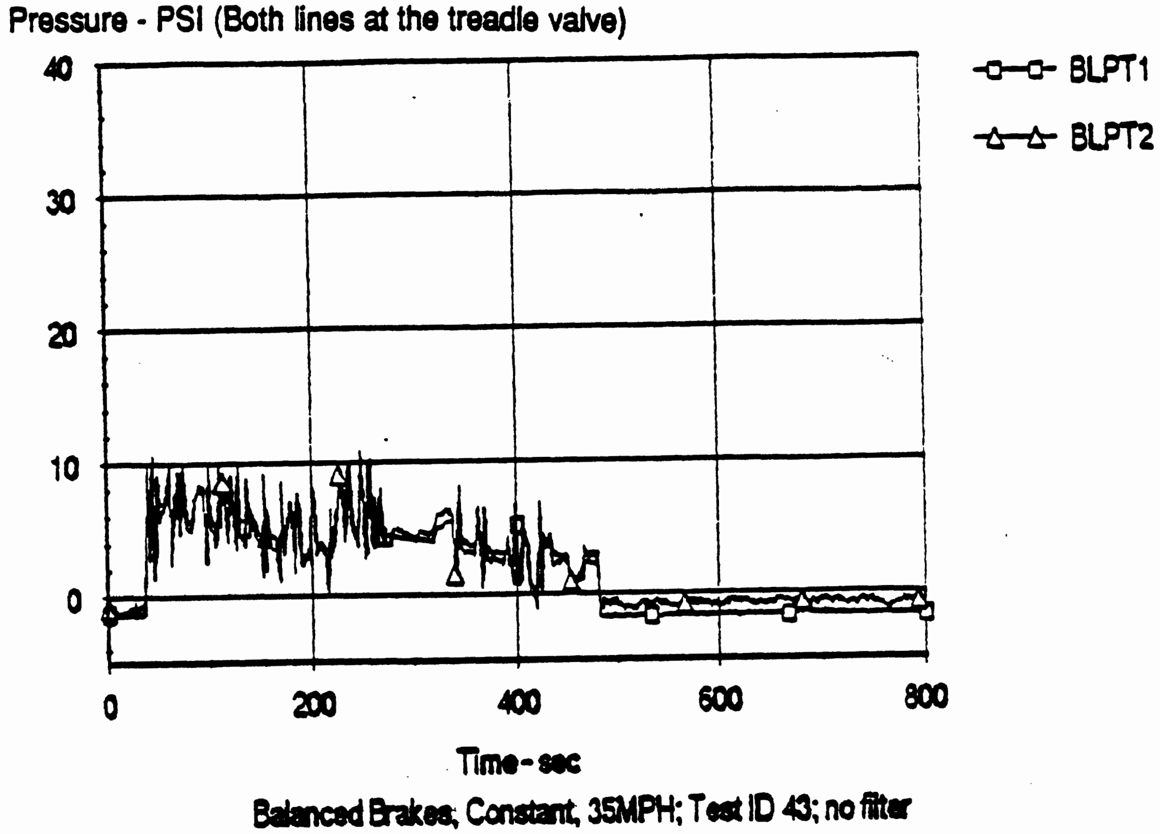


Balanced Brakes, Constant, 35MPH; Test ID 43; BLPA2; no filter



Balanced Brakes, Constant, 35MPH; Test ID 43; no filter

Figure 6b. UMTRI Truck Constant Drag (continued)



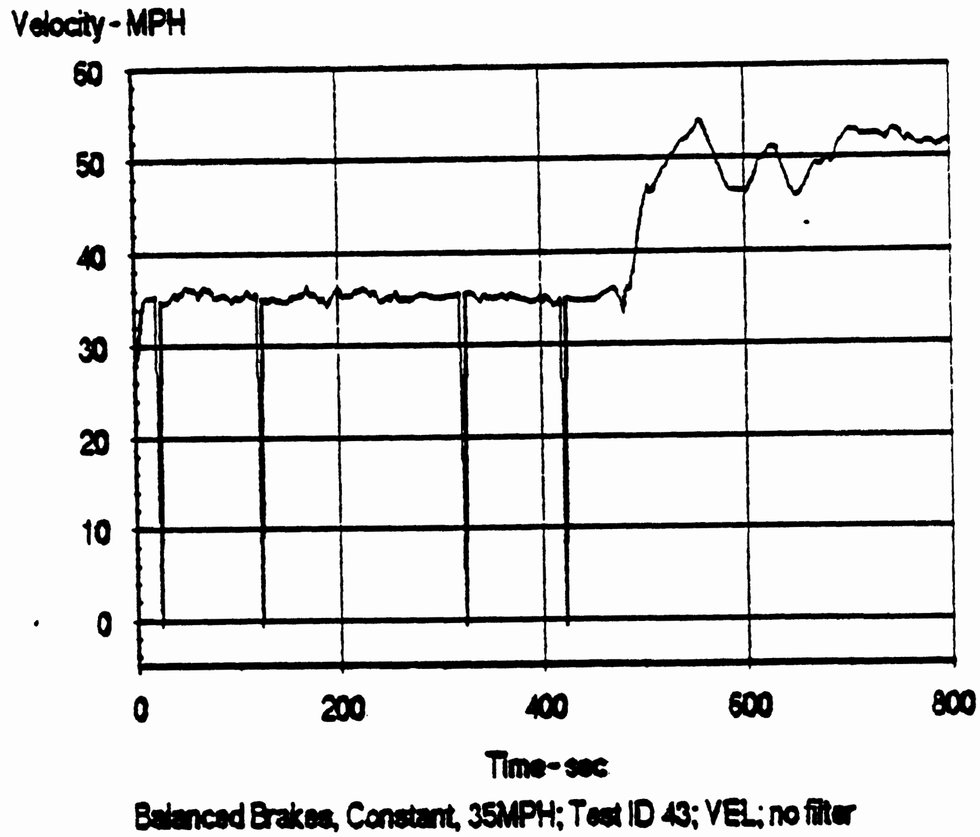


Figure 6c. UMTRI Truck Constant Drag (continued)

Table 2. Brake Temperatures and Strokes for File 42

FILENAME: 42					
TITLE: Balanced Brakes, Pulsed, 35MPH, 6th Gear High, Rear Brakes 1.25" Stroke					
Average Velocity figured from 50 to 375 sec: 35					
Brake Lining Temperature from 50 to 450 sec					
Name	Peak	Time			
LINER-1L	169	388			
LINER-1R	288	359			
LINER-2L	262	357			
LINER-2R	345	357			
LINER-3L	271	439			
LINER-3R	231	438			
Brake Drum Temperature from 50 to 450 sec					
Name	Peak	Time	Averages	Axle Average	
DRUM1-1L	294	358	1L		
DRUM2-1L	333	358	314	Axle 1	
DRUM1-1R	430	358	1R	361	
DRUM2-1R	385	357	408	Axle 2	
DRUM1-2L	327	357	2L	367	
DRUM2-2L	311	357	319	Axle 3	
DRUM1-2R	388	357	2R	388	
DRUM2-2R	442	358	415		
DRUM1-3L	417	394	3L		
DRUM2-3L	407	393	412	**Weighted Brake-Drum Avg.**	
DRUM1-3R	392	395	3R	**373**	
DRUM2-3R	338	357	365		
Stroke (Position) from 50 to 450 sec					
Name	Peak	Time			
BS1L	1.16	335			
BS1R	1.31	335			
BS2L	1.08	334			
BS2R	1.24	334			
BS3L	1.18	334			
BS3R	1.06	334			
Initial Peak Stroke (Position) from 0 to 60 sec					
Name	Peak	Time			
BS1L	0.94	58			
BS1R	0.98	58			
BS2L	0.83	59			
BS2R	0.93	59			
BS3L	0.72	58			
BS3R	0.75	59			
Average Pressure from 50 to 375 sec					
Name	Average				
BLPT1	4.1				
BLPT2	3.9				
BLPA1	3.9				
BLPA2	4.0				
BLPA3	3.9				

Table 3. Brake Temperatures and Strokes for File 43

FILENAME: 43					
TITLE: Balanced Brakes, Constant Drag, 35MPH, 6th Gear High, Rear Brakes 1.25" Stroke					
Average Velocity figured from 50 to 375 sec: 35					
Brake Lining Temperature from 50 to 450 sec					
Name	Peak	Time			
LINER-1L	110	381			
LINER-1R	304	370			
LINER-2L	313	371			
LINER-2R	361	288			
LINER-3L	332	445			
LINER-3R	278	449			
Brake Drum Temperature from 50 to 450 sec					
Name	Peak	Time	Averages	Axle Average	
DRUM1-1L	207	367	1L		
DRUM2-1L	266	367	237	Axle 1	
DRUM1-1R	443	369	1R	322	
DRUM2-1R	372	363	408	Axle 2	
DRUM1-2L	413	367	2L	425	
DRUM2-2L	393	367	403	Axle 3	
DRUM1-2R	393	358	2R	411	
DRUM2-2R	502	343	448		
DRUM1-3L	438	401	3L		
DRUM2-3L	427	402	432	**Weighted Brake-Drum Avg.**	
DRUM1-3R	446	390	3R	**394**	
DRUM2-3R	332	387	389		
Stroke (Position) from 50 to 450 sec					
Name	Peak	Time			
BS1L	0.71	259			
BS1R	0.93	259			
BS2L	0.84	258			
BS2R	0.98	259			
BS3L	0.86	345			
BS3R	0.83	258			
Initial Peak Stroke (Position) from 0 to 60 sec					
Name	Peak	Time			
BS1L	0.62	50			
BS1R	0.67	50			
BS2L	0.60	49			
BS2R	0.70	49			
BS3L	0.51	50			
BS3R	0.58	49			
Average Pressure from 50 to 375 sec					
Name	Average				
BLPT1	6.8				
BLPT2	6.0				
BLPA1	6.5				
BLPA2	5.5				
BLPA3	5.5				

Table 4. Summary of UMTRI Results

Run	Brake Condition	Strategy	Peak Wt. Temp °F	Category Average°F	Max Axle Average°F
31	normal	drag	404	401	#2, 440
32	"	"	396		
43	"	"	394		
49	"	"	411		
29	normal	pulse	351	369	#3, 389
33	"	"	366		
42	"	"	373		
48	"	"	386		
34	misadjustment	pulse	383	382	#2, 394
41	"	"	397		
44	"	"	367		
35	misadjustment	drag	385	378	#2, 400
40	"	"	374		
45	"	"	375		
37	normal	exaggerated snub	378	372	#3, 389
47	"	"	367		
36	misadjustment	exaggerated snub	386	378	#2, 383
46	"	"	371		
38	front limit valves	drag	362	362	#3, 506
39	"	pulse	374	374	#3, 497

that pulsing is as good as dragging (or even slightly better) with regard to maintaining the overall level of brake temperature for this vehicle. From an overall standpoint, the brakes absorb approximately the same proportion of the potential energy due to the mountain regardless of the strategy used, the level of adjustment, or the pressure balance of the brakes.

Inspection of Table 4 indicates that there are differences between the maximum (peak) temperatures from axle to axle. The largest difference occurs when a front limiting valve is used. This is because the front brakes do almost nothing when the limiting valve is employed. The temperature differences from axle to axle are more readily understood when they are plotted for each axle as in Figures 7 through 10. These results show that pulsing tends to result in more uniform temperatures from brake to brake. Even in the case of a front limiting valve (see Figure 10), the pulsing strategy results in the front brakes doing a little work as indicated by a slight temperature rise. From the uniformity of temperature standpoint, pulsing is definitely a better strategy than dragging but the results are not dramatic for this vehicle.

Change in Drum Temperature Baseline

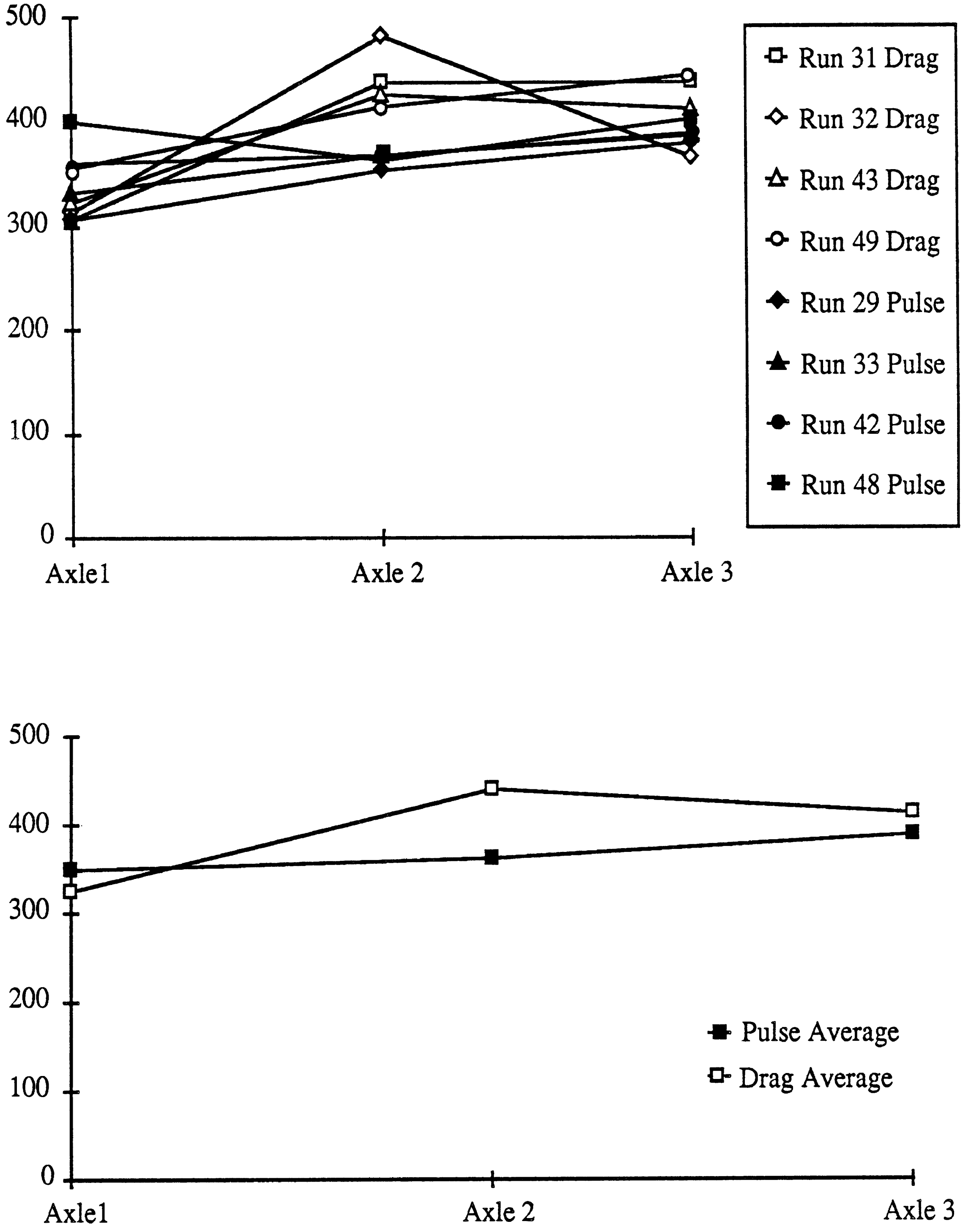
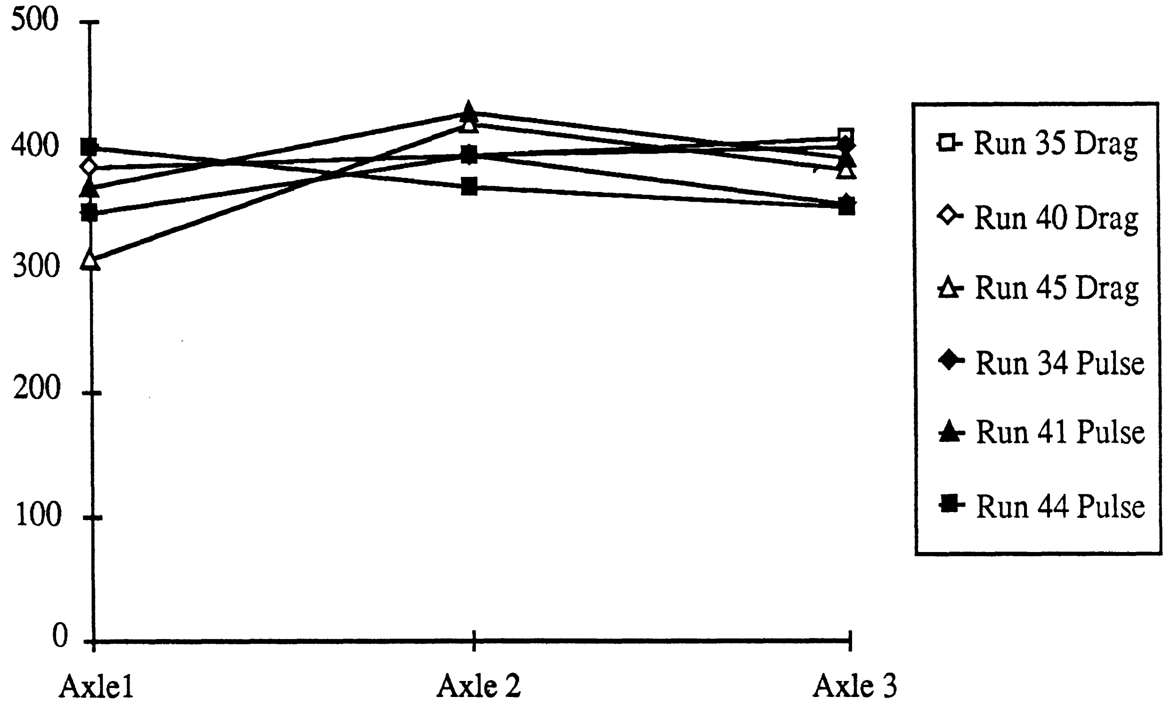


Figure 7. The Influence of Braking Strategy for the Truck

Change in Drum Temperature Misadjusted Brakes



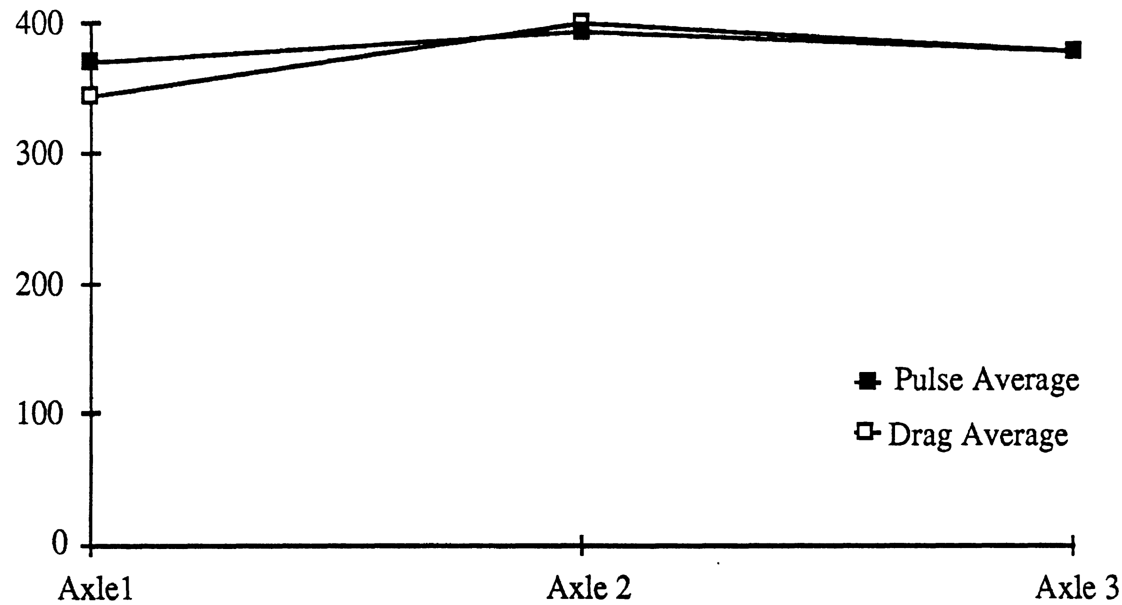
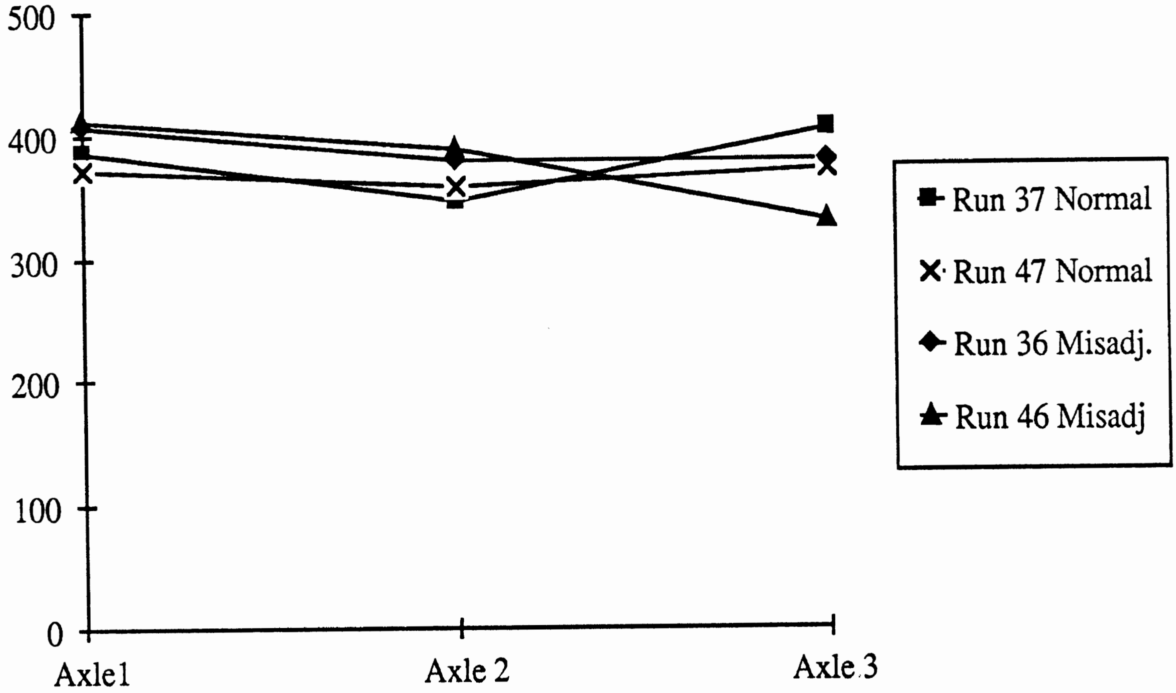


Figure 8. The Influence of Misadjustment for the Truck

Change in Drum Temperature Exaggerated Snub



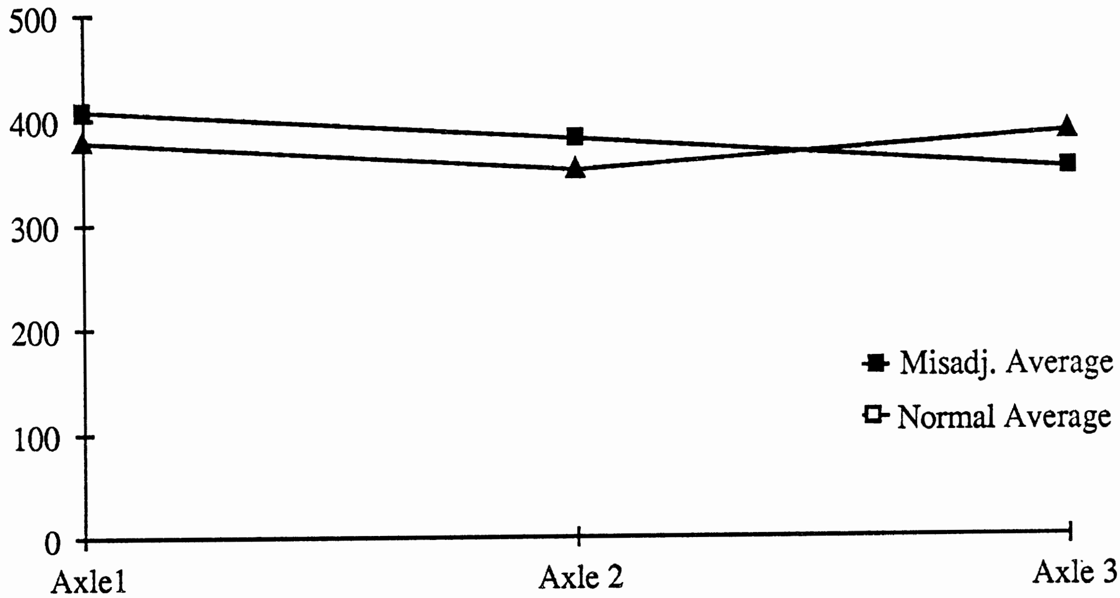


Figure 9. Exaggerated Snubbing ± 5 mph

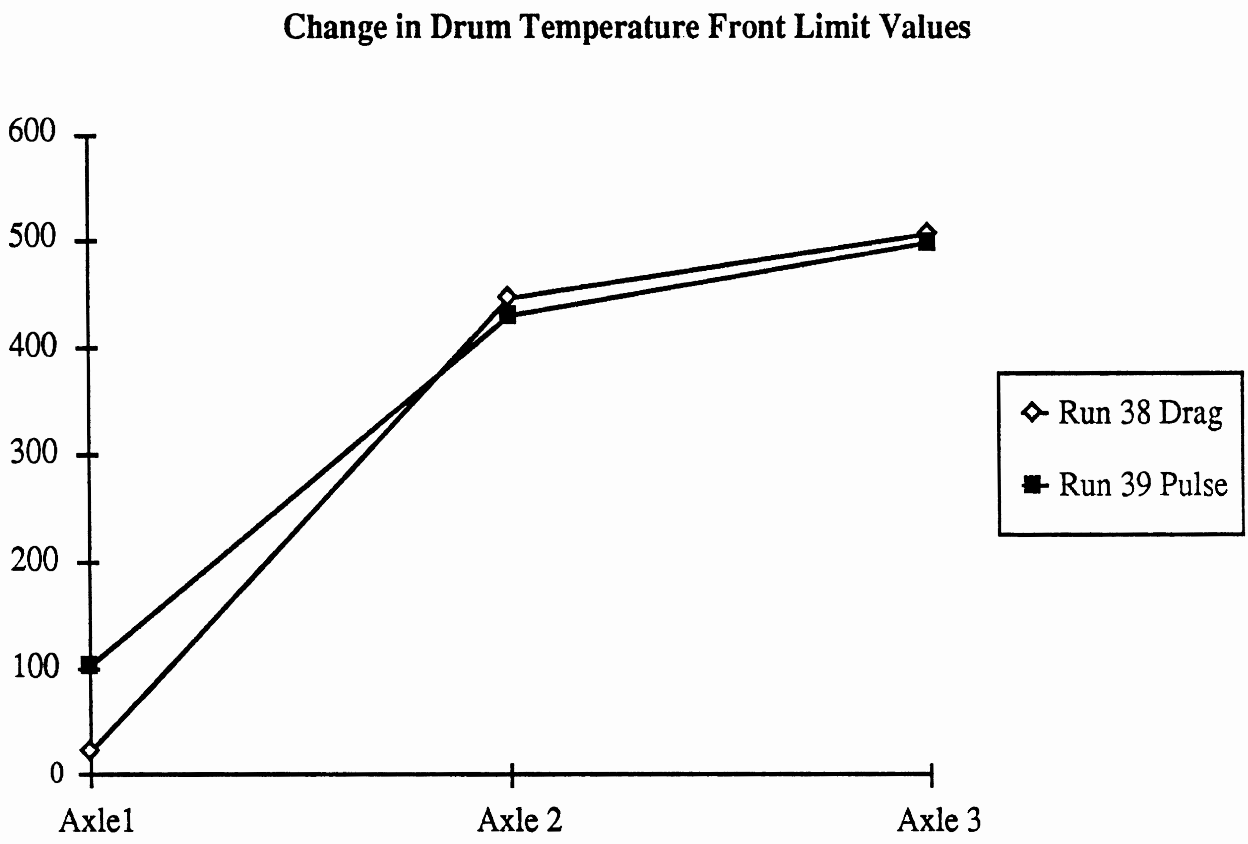


Figure 10. The Influence of a Front Limit Valve on Brake Temperatures

3.2 Results for the NHTSA tractor semitrailer (3-S2).

This vehicle also performed tests using both drag and snub strategies. Figures 11 and 12 provide examples of results. As illustrated in Figure 9, the constant-drag strategy produced a wide diversity in temperatures from brake to brake. The brake temperatures were much more uniform when the pulsing (snubbing) strategy was used (see Figure 12). As indicated in these figures, the trailer brakes reached high temperatures. When the temperatures were quite high, the strokes became long—over 2 in when snubbing was used. These results were obtained even though the control speed was at 20 mph in these runs. Almost 800 sec were needed to reach the bottom of the mountain.

The runs from the 3-S2 tractor semitrailer have been processed for weighted average temperature (see Figure 13). For this vehicle it appears that the dragging strategy maintains lower temperatures in most cases. However, these differences are usually small and sometimes the snubbing strategy is better. We do not consider the differences to be grounds for recommending one strategy over the other. In fact, if some brakes get very hot they will cool more due to radiation, and this additional cooling may lead to a lower overall weighted temperature.

When the constant-drag method was employed, the brakes on the tractor's drive axles of the 3-S2 did very little braking, as indicated by the low temperatures appearing for the drive axles in Figure 14. Balance level B was particularly bad in this regard because the threshold pressure was 12.1 psi (see Table 1). In contrast, when the pulsing/snubbing strategy was used, the drive-axle brakes did an appreciable amount of the braking and the temperatures attained at the trailer's axles tended to be noticeably lower than those attained when a dragging strategy was used. As in the case of the truck, the pulsing strategy produced a more uniform distribution of brake temperatures and each brake came closer to doing its fair share of the work.

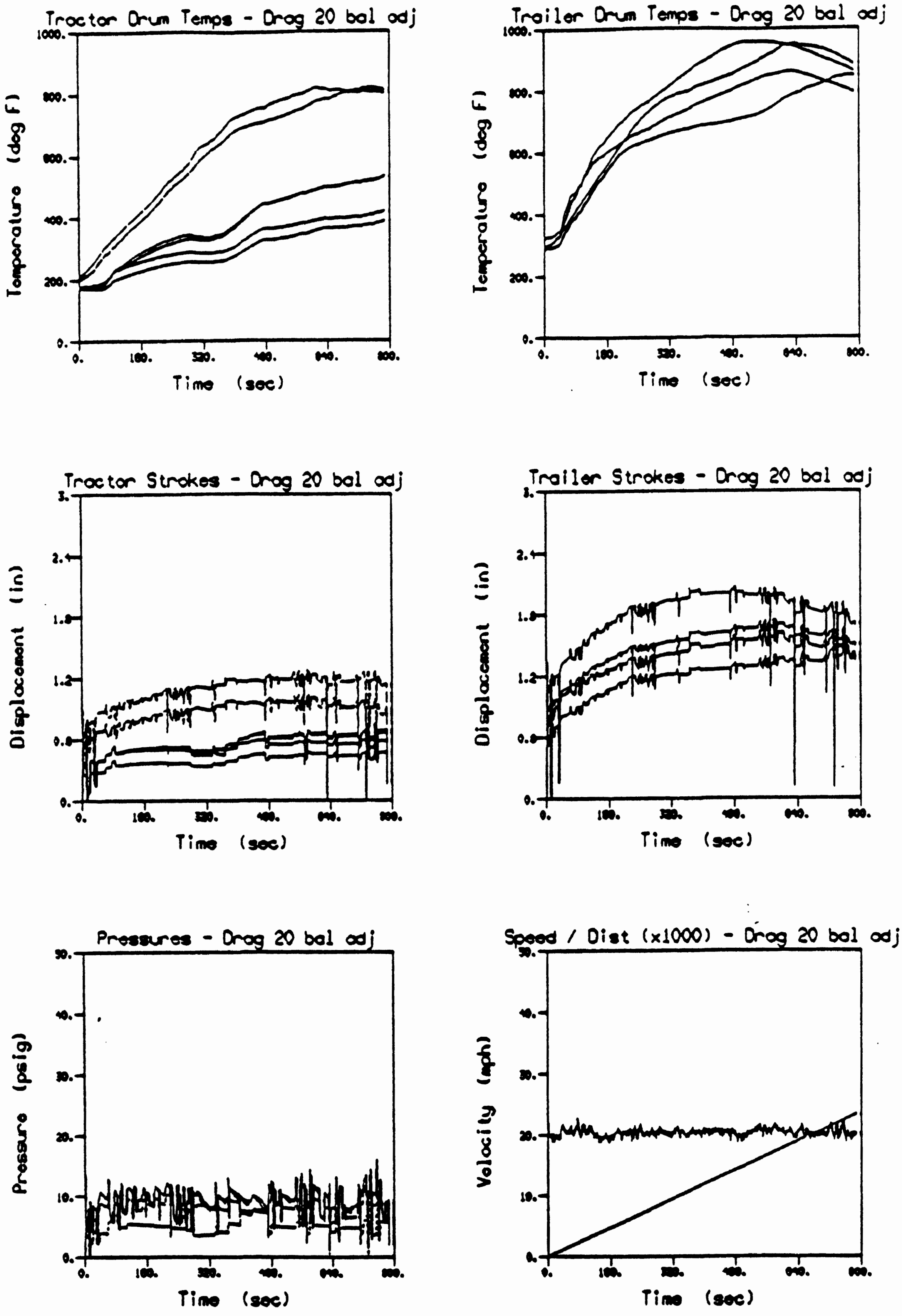


Figure 11. NHTSA 3-S2 Constant Drag

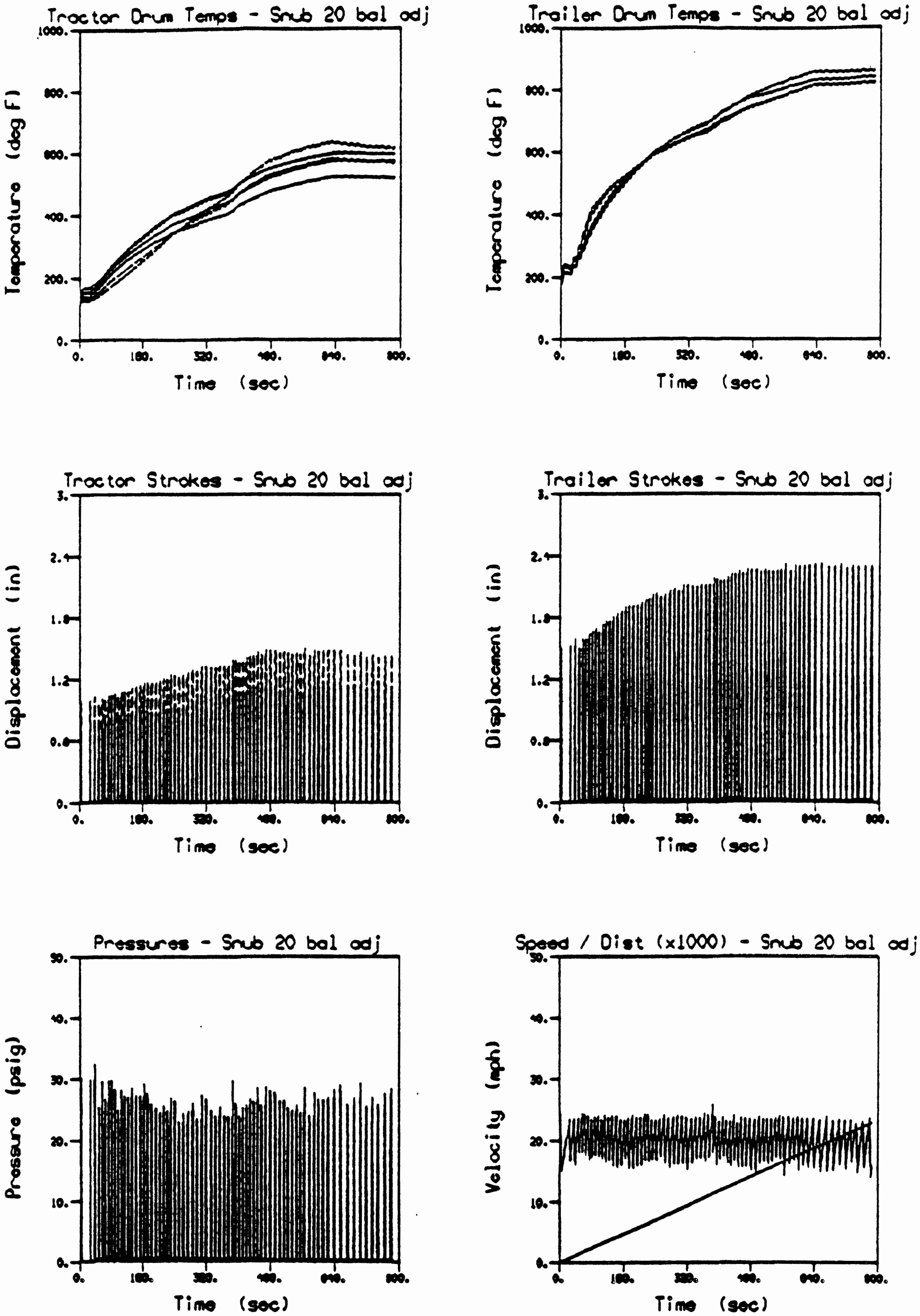
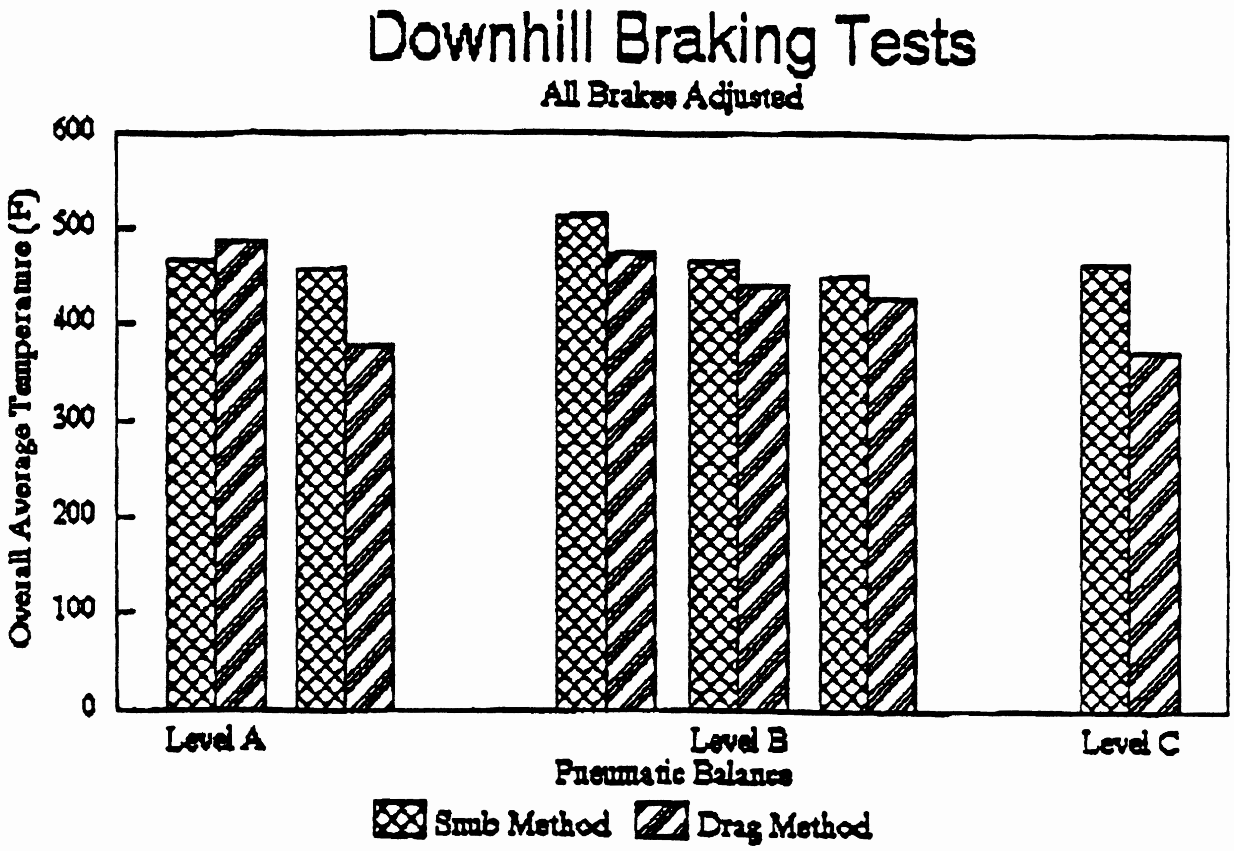


Figure 12. NHTSA 3-S2 Pulsing Test



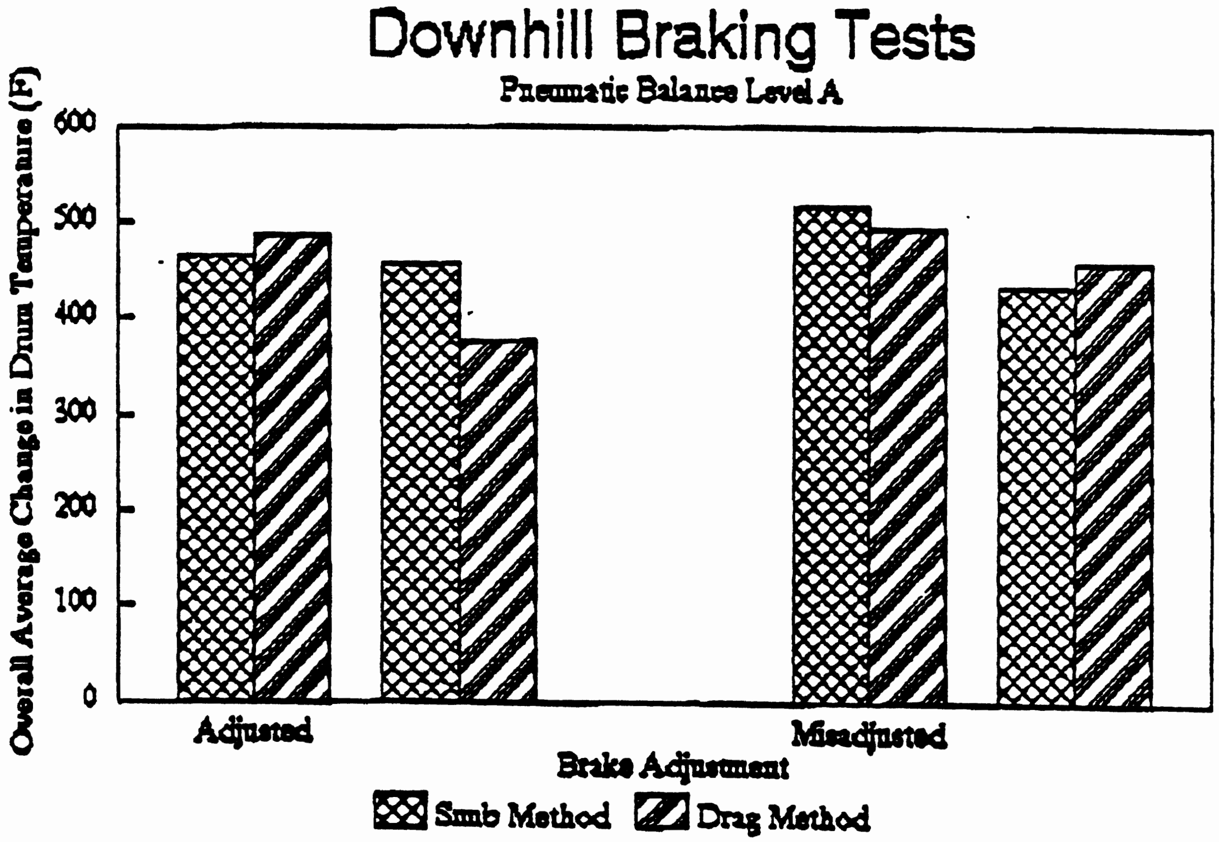


Figure 13. Weighted Average Drum Temperatures (3-S2)

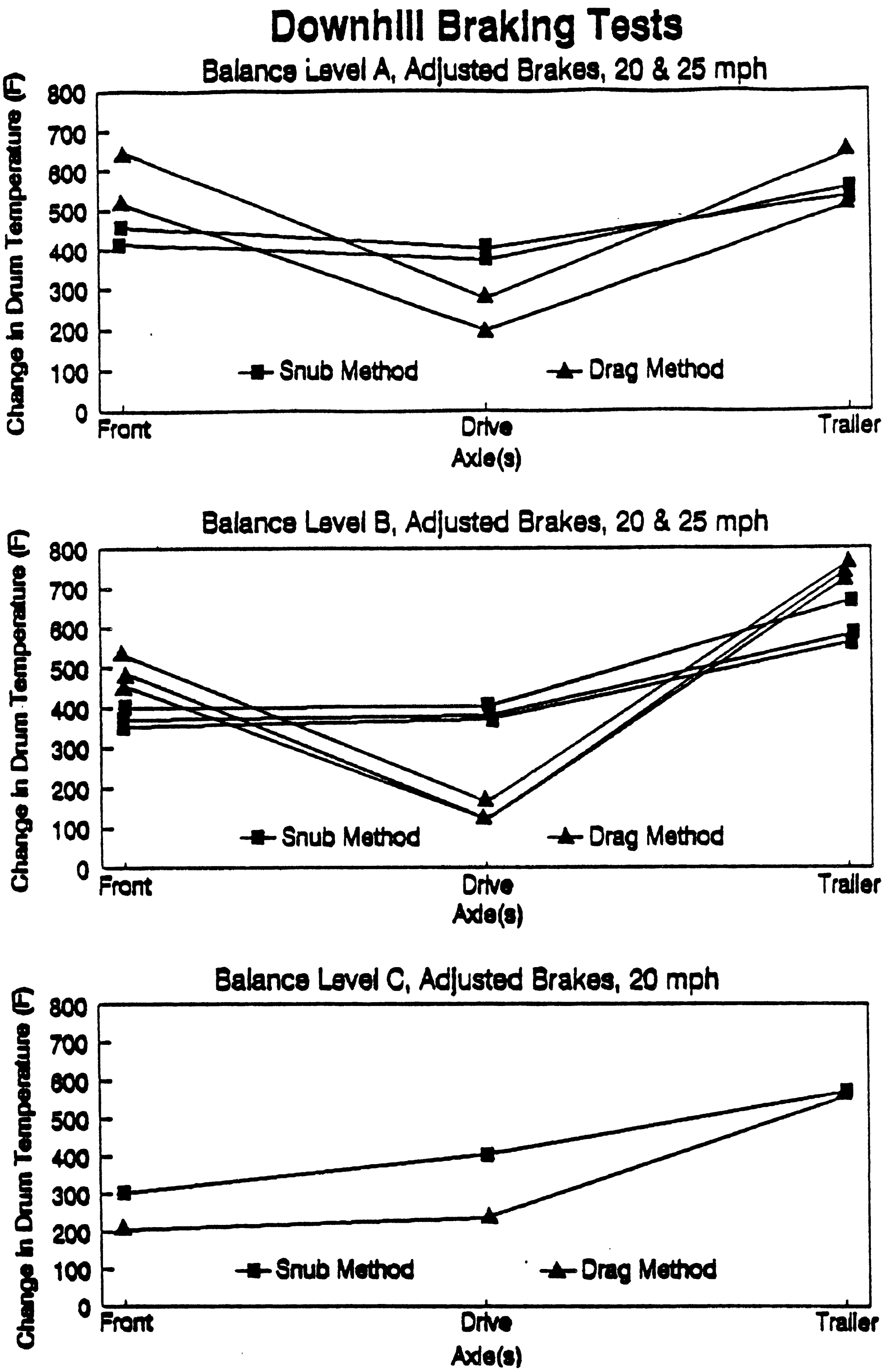


Figure 14. Average Temperatures by Suspension Group (3-S2)
The Influence of Balance Level

Figure 15 provides results obtained when the drive axles' brakes are set to have an applied stroke of 2 in at 100 psi. (This did not change the temperatures much—partially because the drive-axle brakes did a limited amount of the total braking on this vehicle.)

Figure 16 gives an indication of the pressure levels used during the braking tests. The low level of pressure at the drive axles is apparent for the constant drag strategy.

The NHTSA vehicle was equipped to obtain stopping distance measurements. Stopping distance tests were performed on a nearly level section of highway at the bottom of the mountain. These tests were from an initial velocity of 35 mph using 60 psi brake pressure. A complete set of results is presented in Table 5.

The results in Table 5 run from a minimum of 89 ft to a maximum of 130 ft (which correspond to deceleration levels of 0.46 g and 0.32 g, respectively). The differences in stopping performance may be related to (a) control speed and (b) whether the brakes are misadjusted.

For those runs at 25 mph in which the brakes were not misadjusted, the distances were longer than the comparable runs at 20 mph. This is to be expected since the brake temperatures were higher at 25 mph than they were at 20 mph. The influence of temperature on drum expansion and hence stroke is illustrated in Figure 17, which shows stroke during the 60 psi stops.

The last graph on the second page of Figure 17 shows the strokes at each suspension location for cases with misadjusted brakes. Examination of this graph for misadjusted brakes indicates that the stroke is beyond the readjustment point and well into the range where braking force will be considerably reduced at 60 psi for both the drive-axle and the trailer axle brakes. The stroke is large at the drive-axle brakes because they are misadjusted. The stroke is large at the trailer brakes because they are very hot. The combination results in poor braking performance for those runs in which misadjustment appears (runs e, f, k, l, o, and p in Table 5).

The results for runs o and p indicate that, under conditions of (a) misadjusted brakes on the tractors drive axle and (b) pneumatic balance that reduces the relative amount of work done by the front axle brakes (i.e., Case C), a longer stopping distance was measured after snubbing as compared with dragging the brakes. However, it is not fair to compare runs o and p because in the dragging run p the trailer brake temperature became large enough to cause the driver to stop using the foundation brakes. The net effect was an incremental increase in stopping distance after the snubbing test.

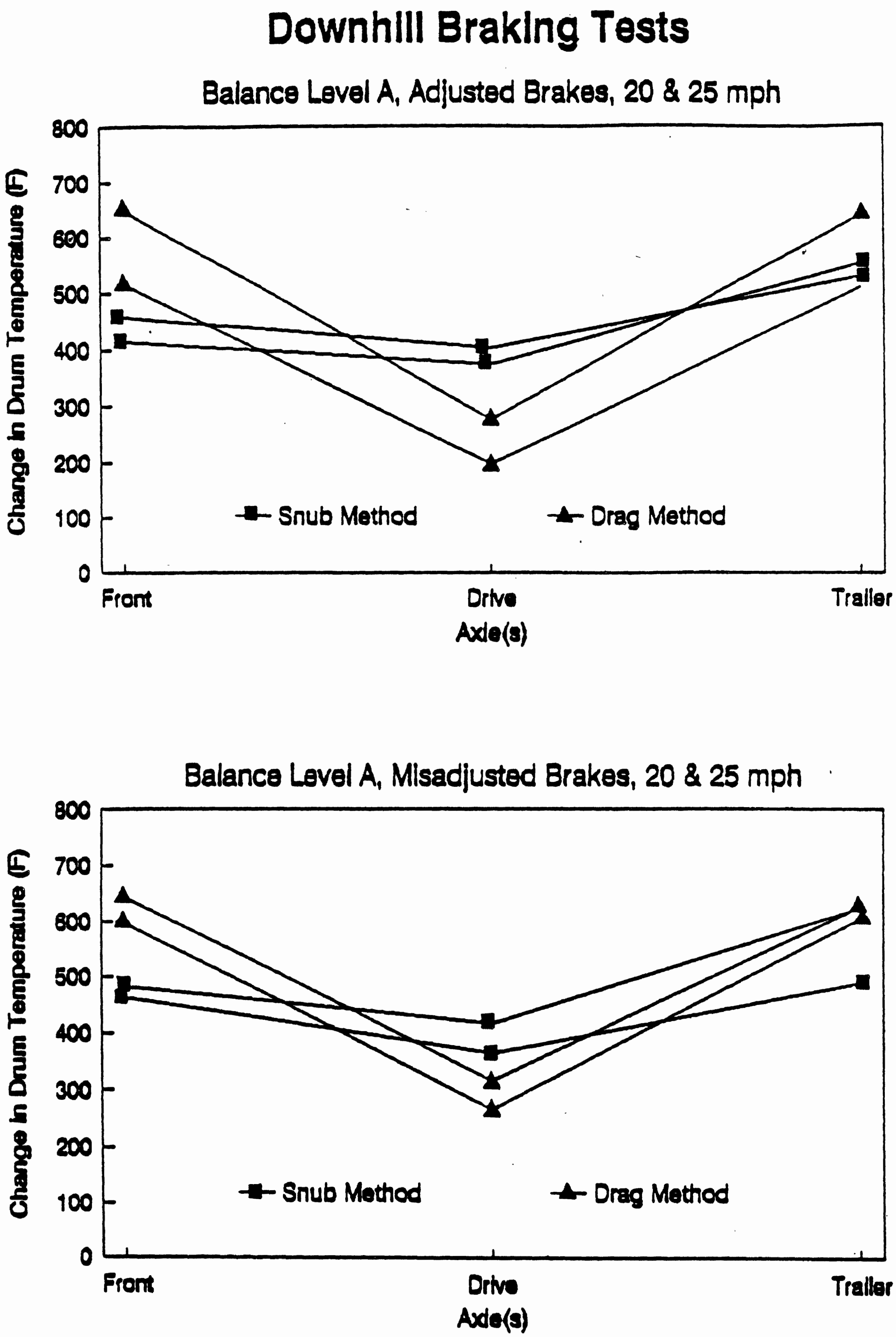


Figure 15. The Influence of Misadjustment on the 3-S2

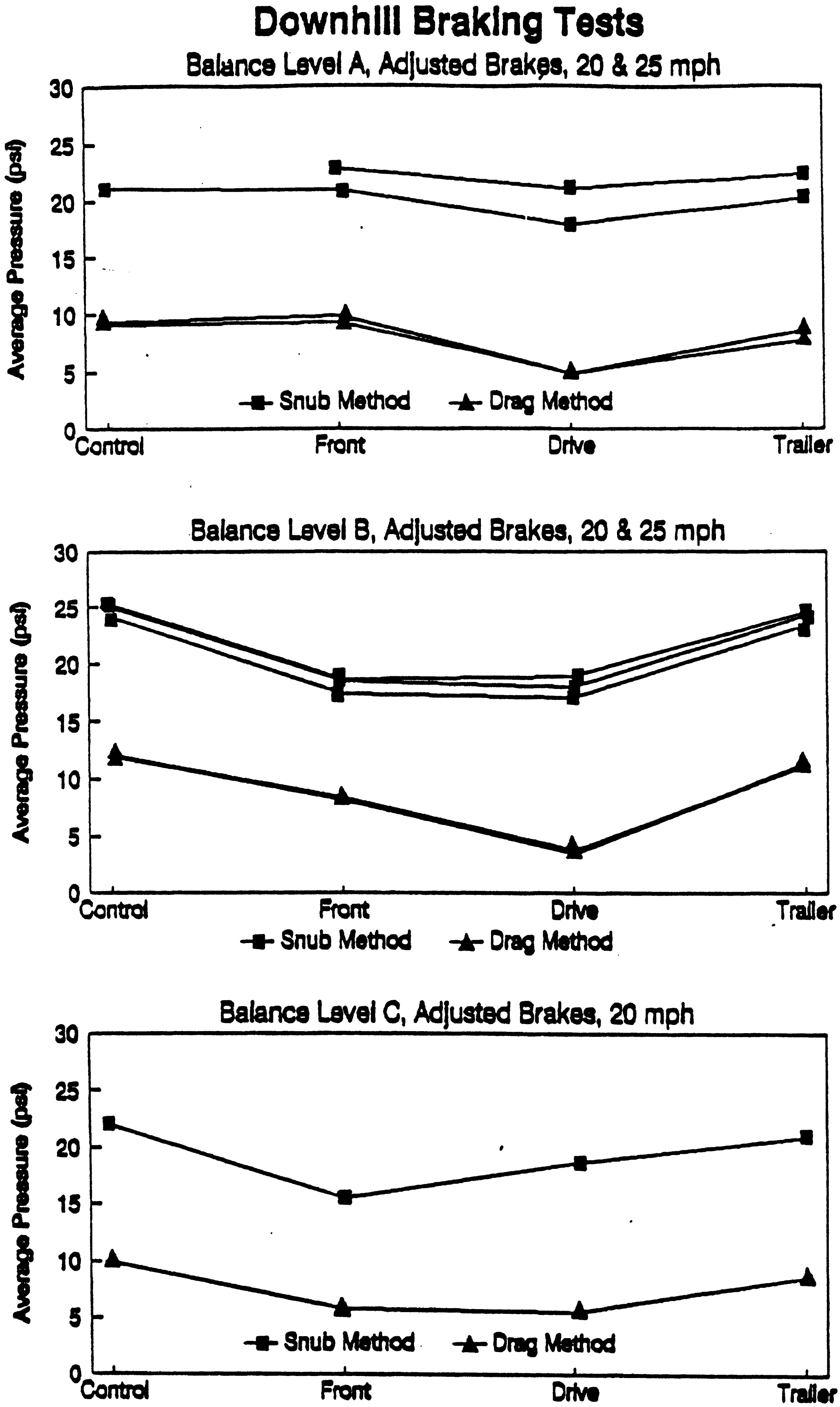
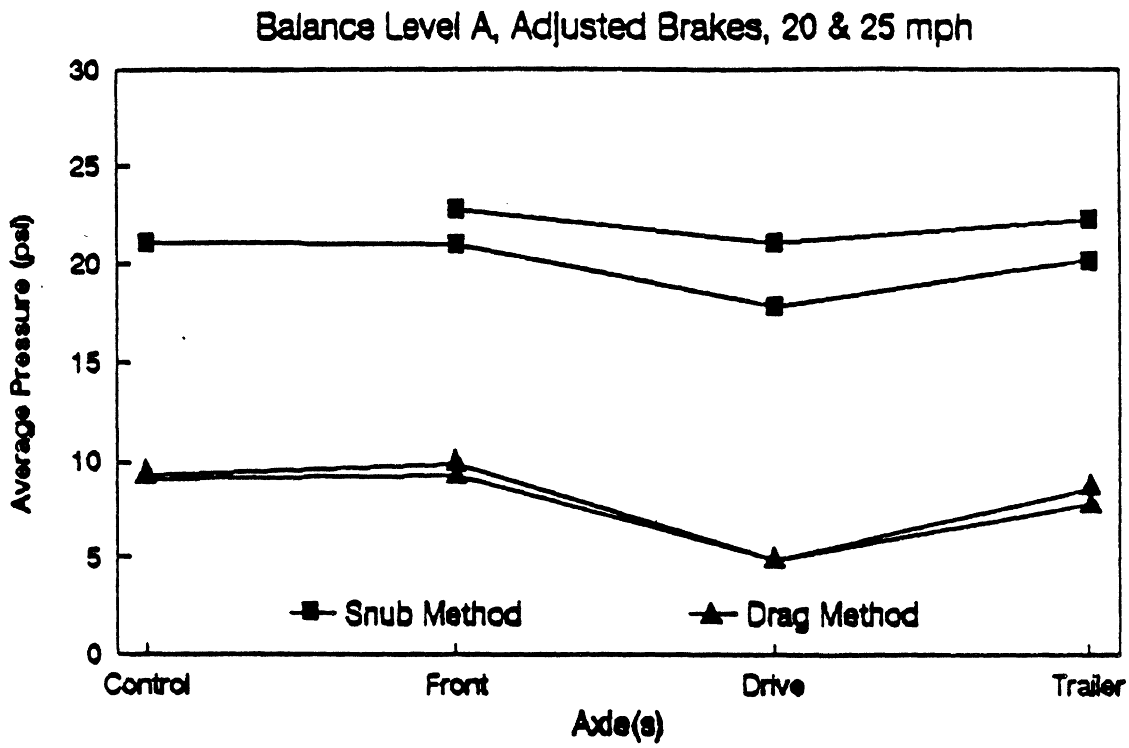


Figure 16. Pressure During Testing of the 3-S2

Downhill Braking Tests



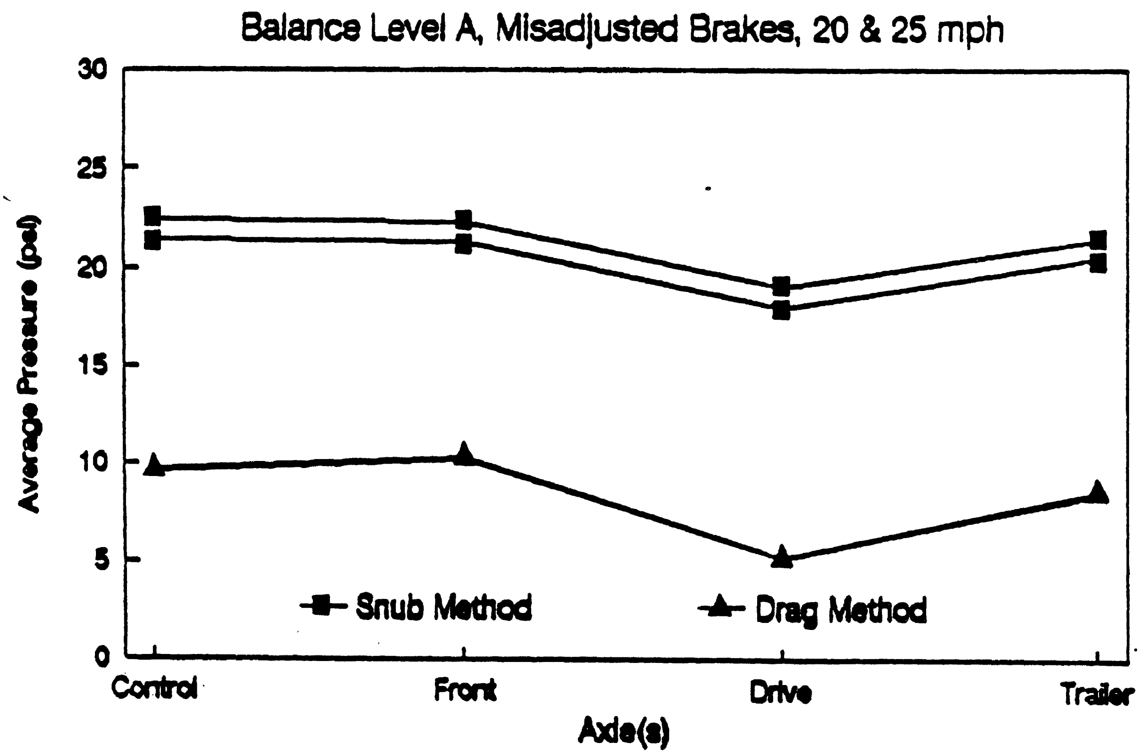


Figure 16. Pressure During Testing of the 3-S2 (continued)

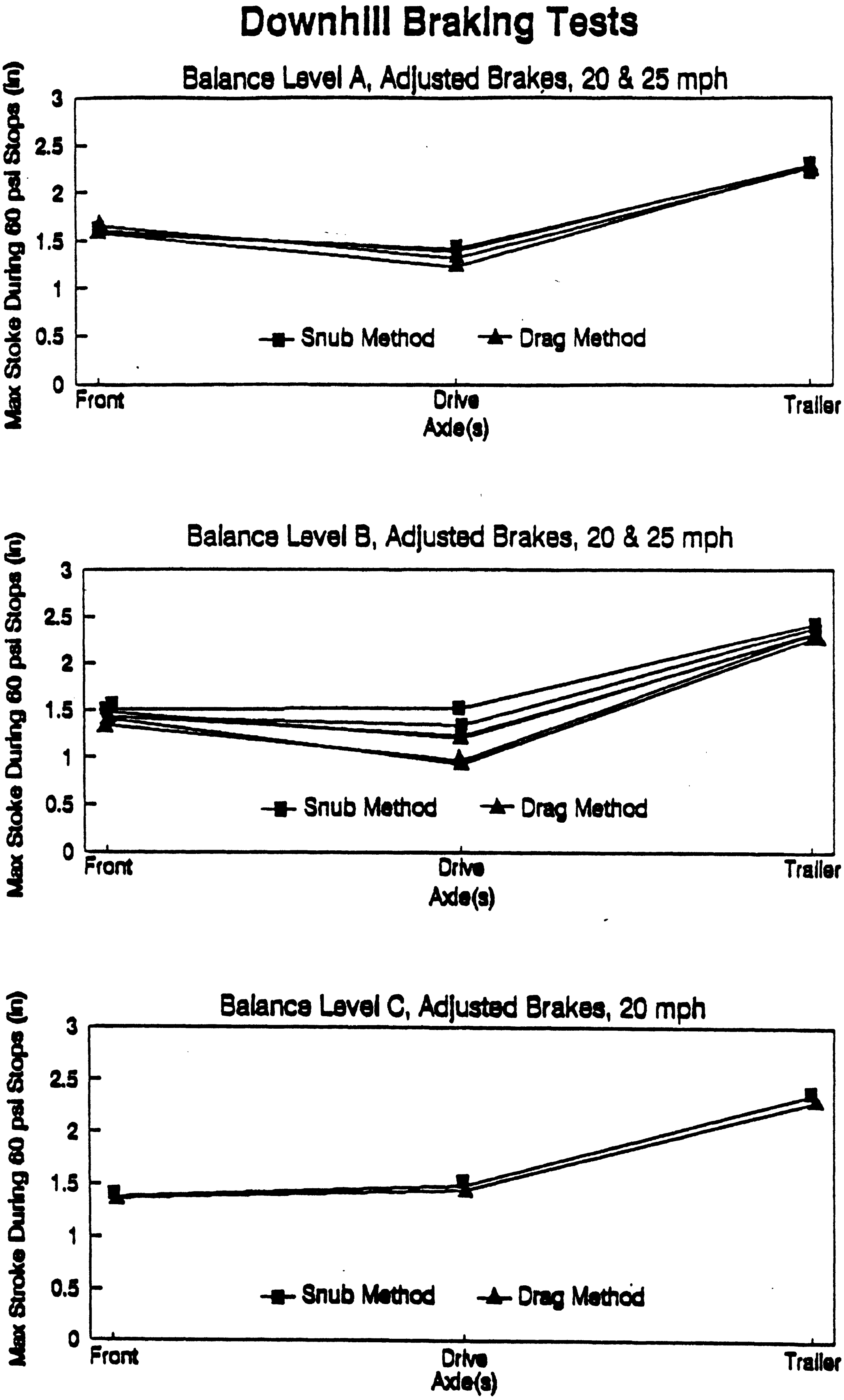
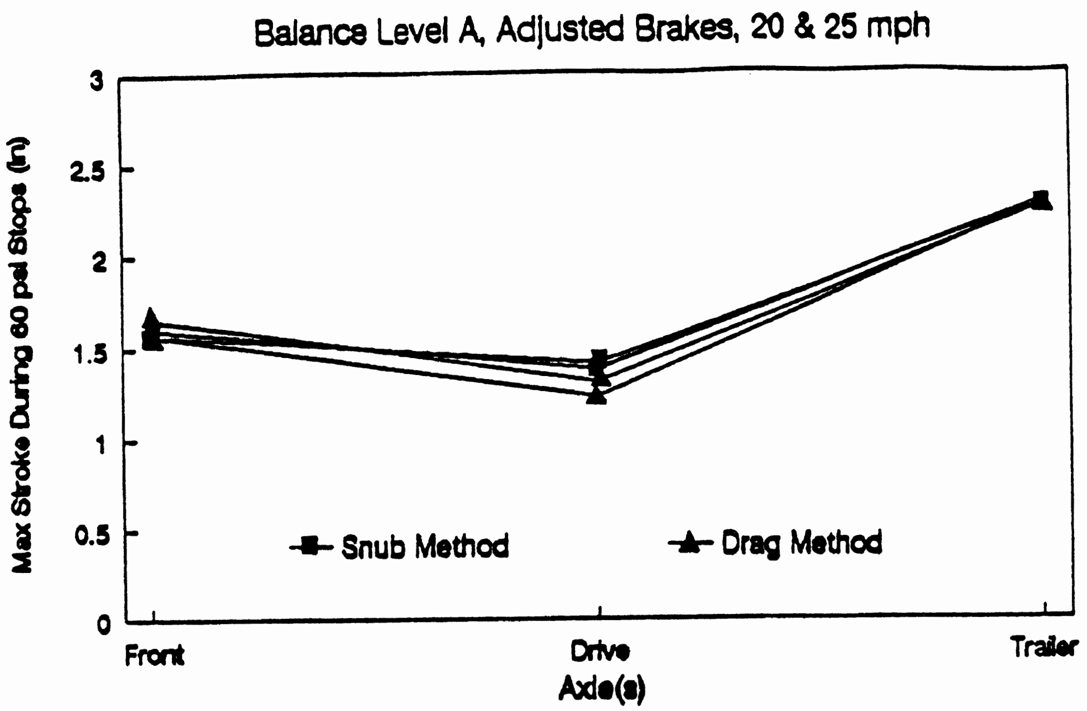


Figure 17. Stroke During Braking After a Mountain Descent (3-S2)

Downhill Braking Tests



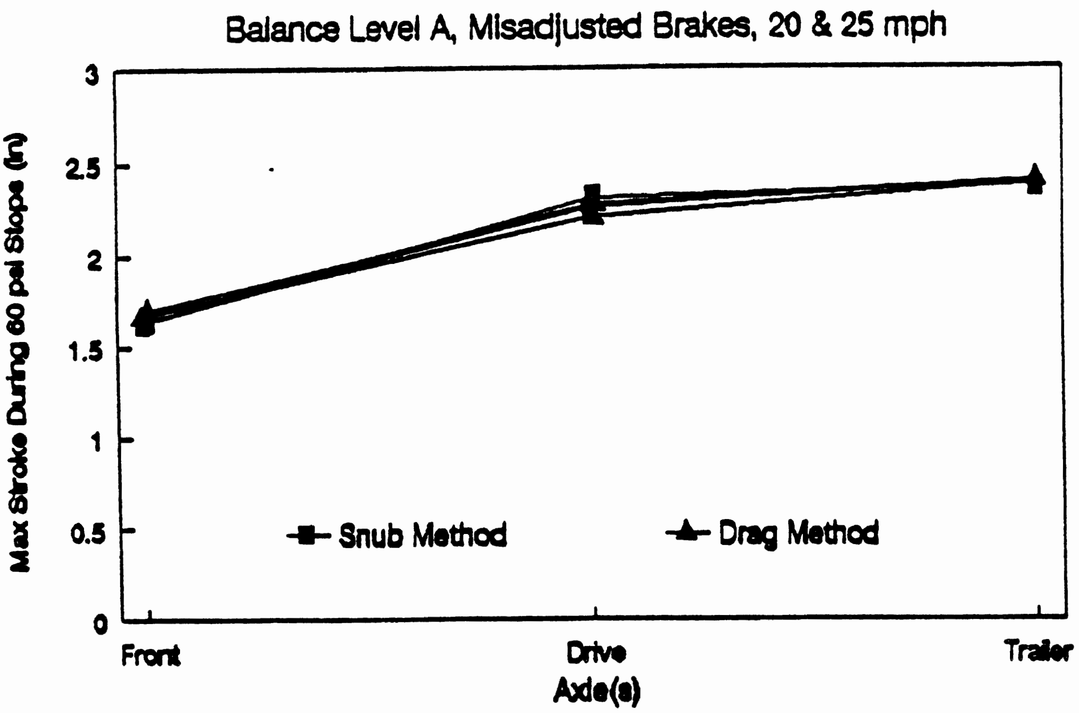


Figure 17. Stroke During Braking After a Mountain Descent (3-S2) (continued)

Table 5. 3-S2 Stopping Distances Attained in 60 psi Stops from 35 mph After Descending the Mountain

Run	Balance	Misadjustment	Strategy	Control, Speed,mph	Hot Distances ft. (2 Repeats)	
a)	A	no	Snub	25	103	101
b)	A	no	Drag	25	101	99
c)	B	no	Snub	25	101	100
d)	B	no	Drag	25	100	101
e)	A	yes	Drag	25	121	120
f)	A	yes	Snub	25	122	124
g)	B	no	Snub	20	89	90
h)	B	no	Drag	20	92	93
i)	A	no	Drag	20	94	99
j)	A	no	Snub	20	96	92
k)	A	yes	Snub	20	114	113
l)	A	yes	Drag	20	114	112
m)	B	no	Drag	20	107	103
n)	B	no	Snub	20	106	105
o)	C	yes	Snub	20	129	130
p)*	C	yes	Drag	20	122*	119*
q)	C	no	Drag	20	91	88
r)	C	no	Snub	20	96	93

*braking aborted after descending 3/4 of the mountain

Aside from the circumstances associated with balance level C, the influence of snubbing versus dragging on stopping distance was small. Key factors for producing longer stopping distances are (1) misadjusted brakes on the tractor combined with pneumatic balance that will produce very hot trailer brakes (of course, the same result could be obtained with misadjusted trailer brakes combined with a pneumatic balance that produced very hot brakes on the tractor) and (2) the control speed used in descending the mountain.

4.0 RESULTS FROM MOBILE DYNAMOMETER TESTS OF INDIVIDUAL BRAKES

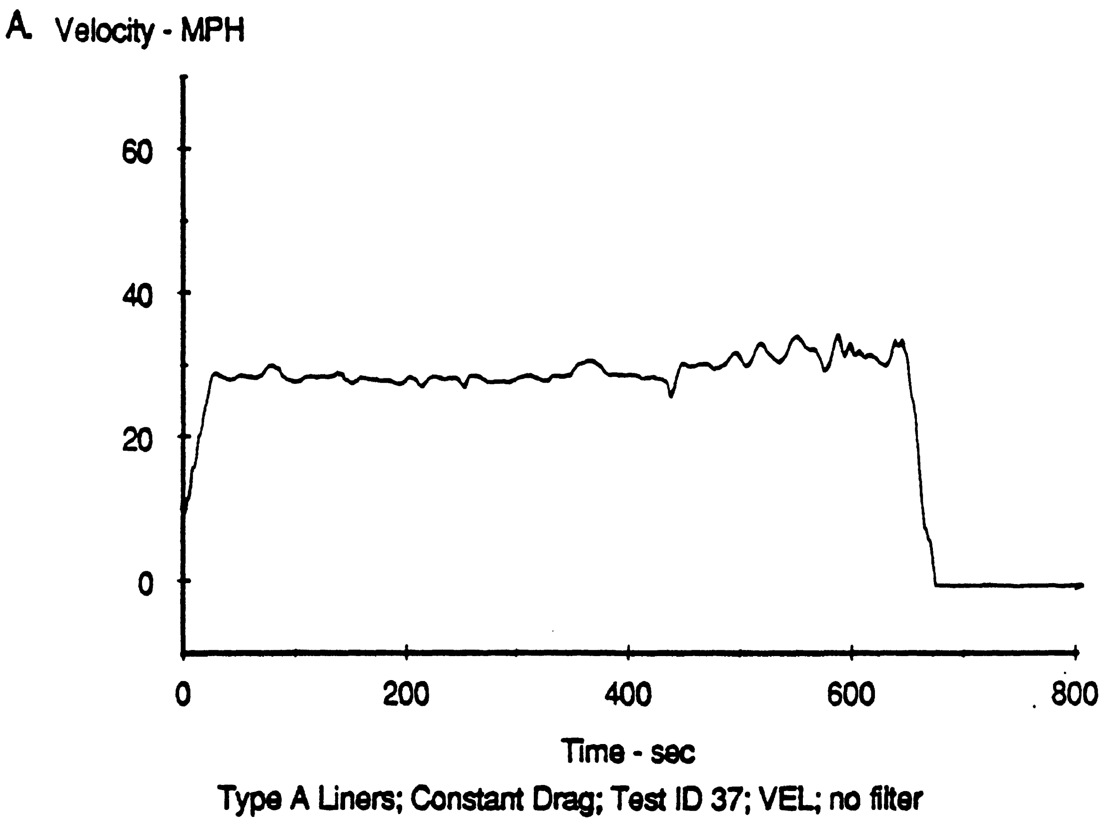
4.1 Cooling rates for dragging and snubbing strategies.

The first set of mobile dynamometer experiments provided data for use in comparing cooling rates for dragging and snubbing strategies. In these experiments, the mobile dynamometer was traveling at 30 mph to simulate a mountain-descent control speed of 30 mph.

The brake under test was applied at a constant torque of 8,000 in lb to simulate a constant dragging strategy. This torque was applied for a sufficient length of time (approximately 400 sec) to raise the average outside drum-temperature to over 600° F. (See Figure 18 for examples of time histories of data from a typical experimental run simulating the dragging strategy on the mobile dynamometer.)

To simulate a snubbing (also referred to as "pulsing") strategy, the brake was applied in "pulses" of torque reaching approximately 24,000 in lb. (See the brake-torque time-history in Figure 19) Since the pulses last for about 3 sec followed by 6 sec with no braking, the average torque during pulsing was approximately the same as the constant torque used in the dragging experiments.

The data obtained from four repeats of the drag test and four repeats of the snub (pulse) test have been analyzed to estimate the cooling rates of the brake during the experimental runs. The analysis procedure is based upon the physical model of heat flow presented in Appendix D. The computation of cooling rate involves calculating two integrals from the time histories of the test data. The work done by the brake (i.e., the energy absorbed by the brake) is the integral of the product of brake torque times rotational speed. The other integral computed in processing the data is the integral of brake drum temperature. Using these two integrals (and also data on the initial and final drum temperatures and braking times; and values for ambient temperature, specific heat, and drum mass), the experimental data can be used to determine the cooling rate while braking is occurring. The results are presented in Table 6.



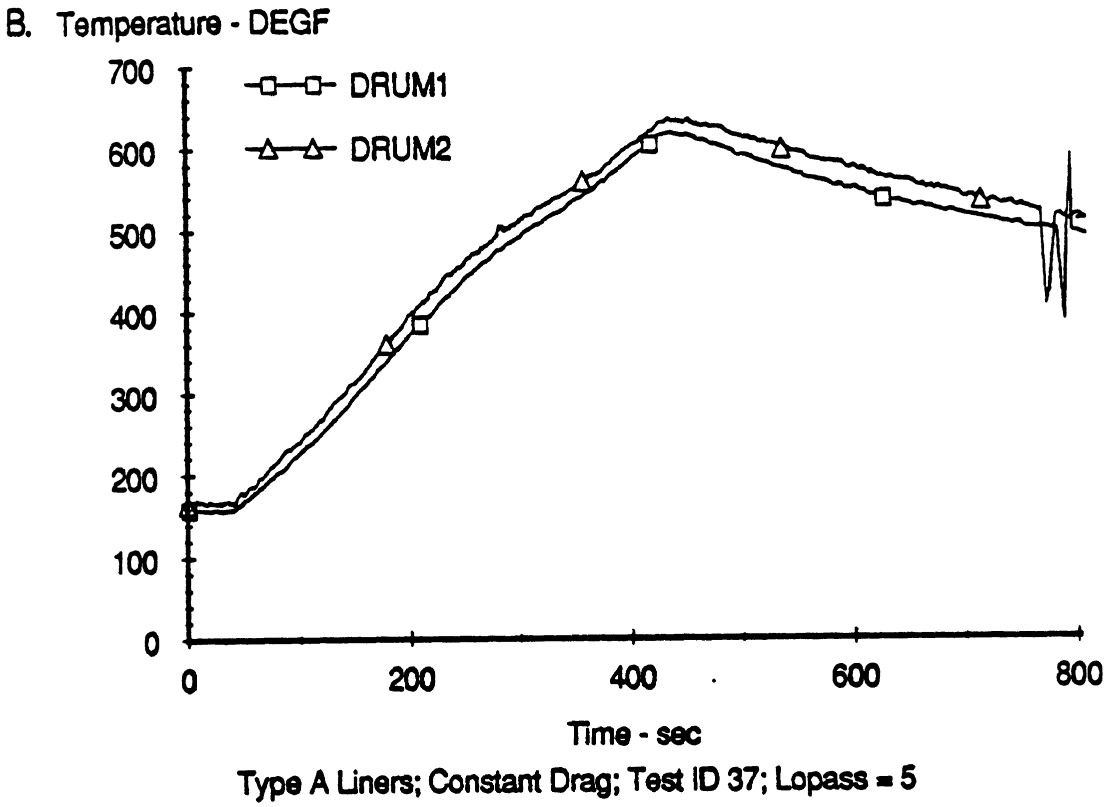


Figure 18. Cooling Rate Experiment, Drag Test

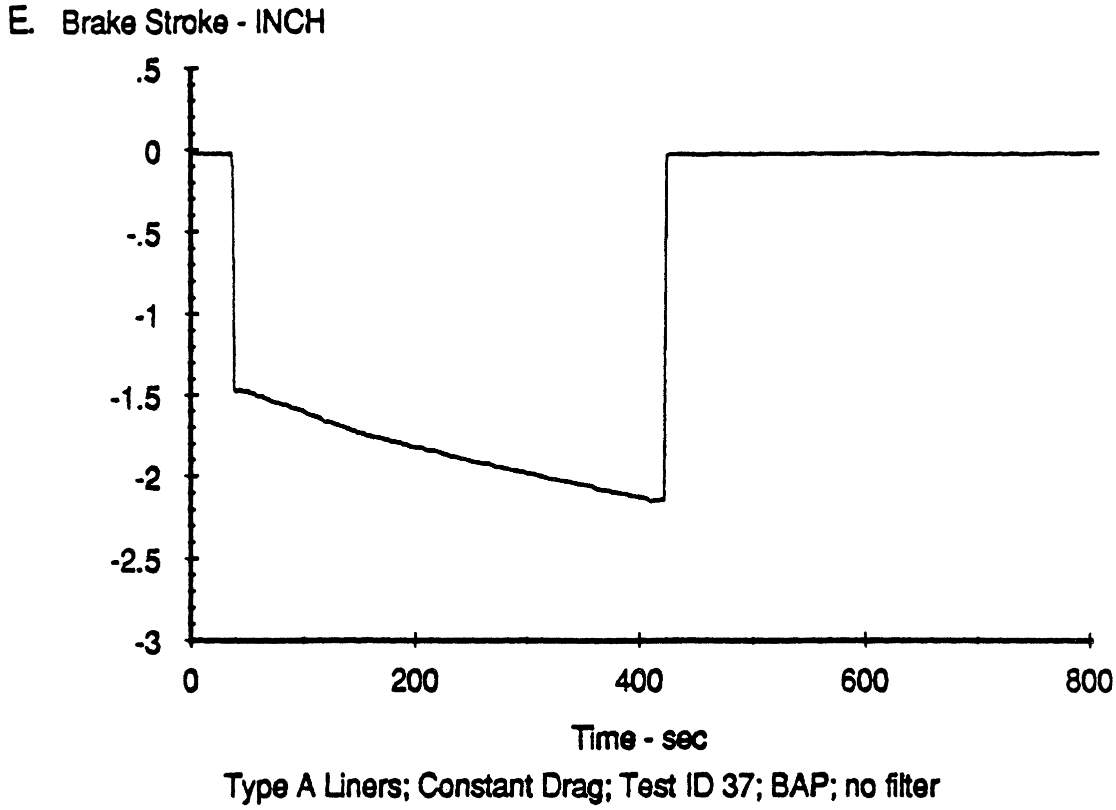
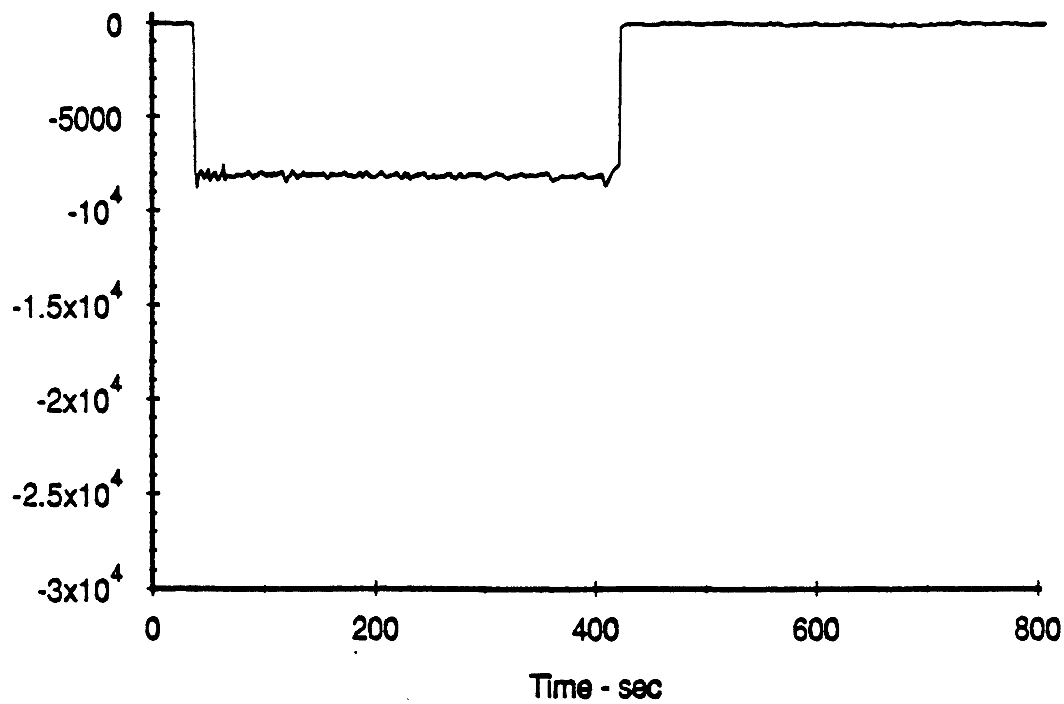


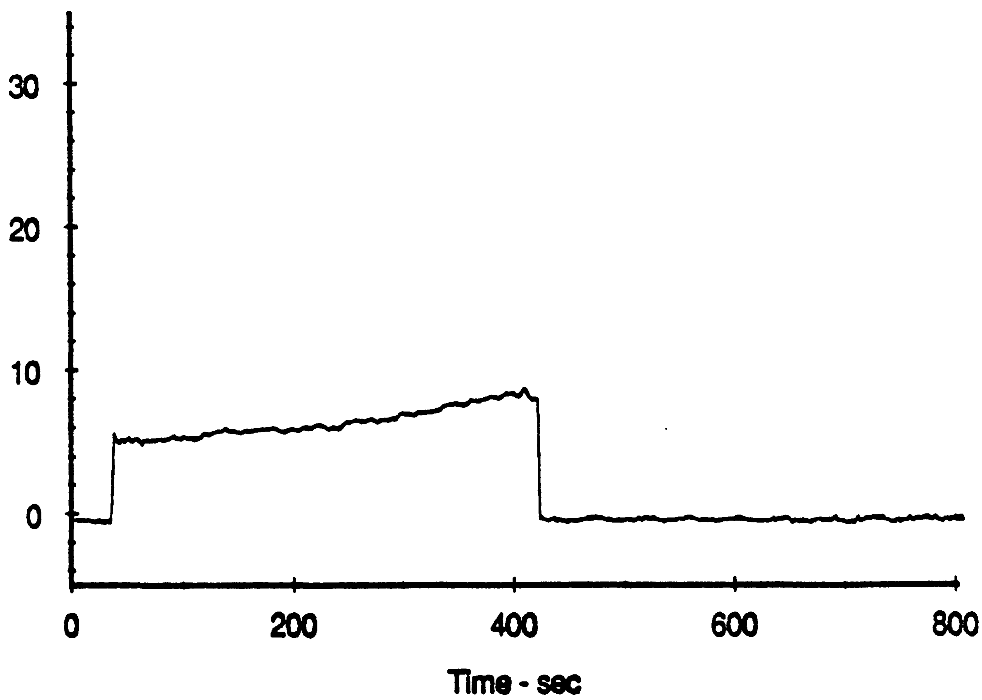
Figure 18. Cooling Rate Experiment, Drag Test (continued)

C. Brake Torque - IN-LBS



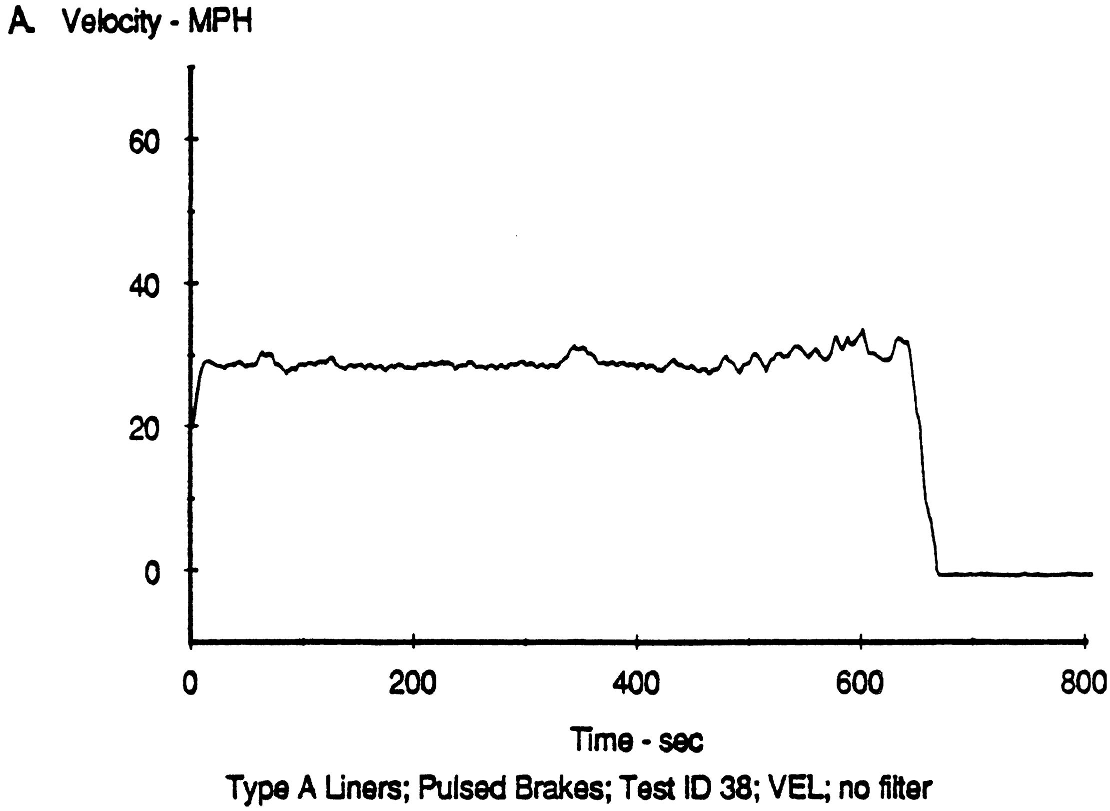
Type A Liners; Constant Drag; Test ID 37; TB; no filter

D. Brake Line Pressure - PSI



Type A Liners; Constant Drag; Test ID 37; BLP; no filter

Figure 18. Cooling Rate Experiment, Drag Test (continued)



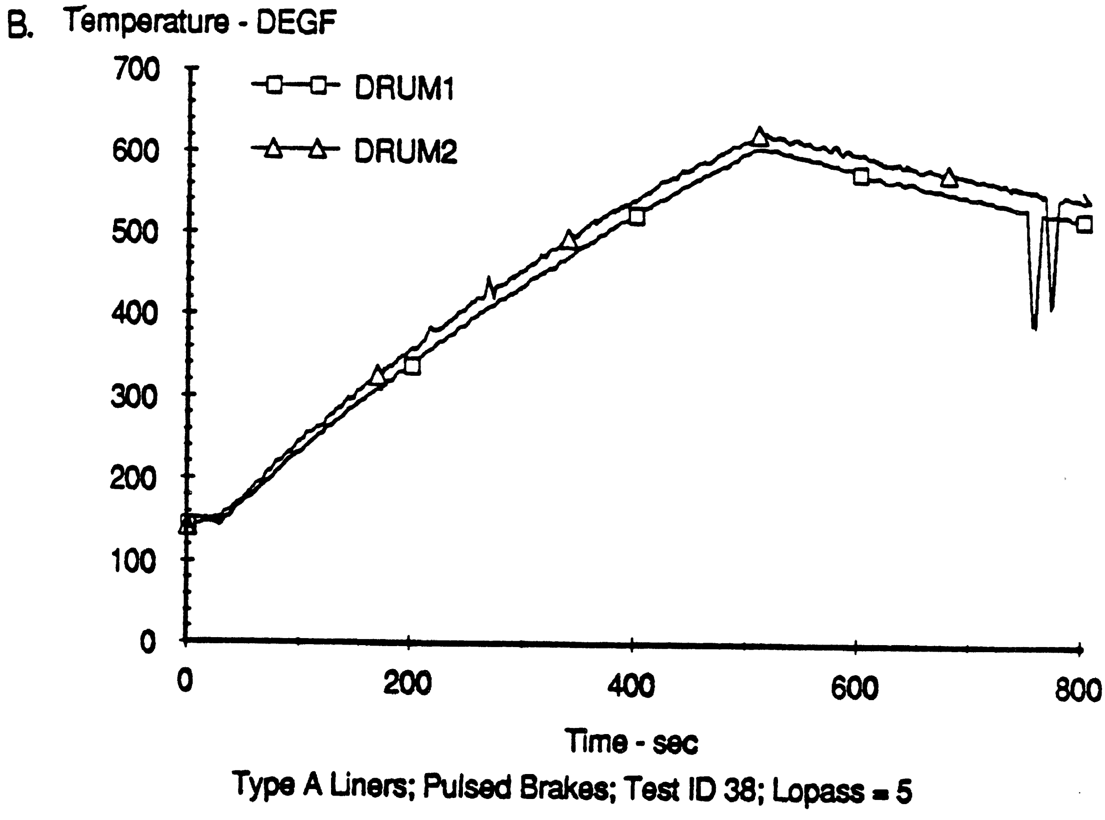
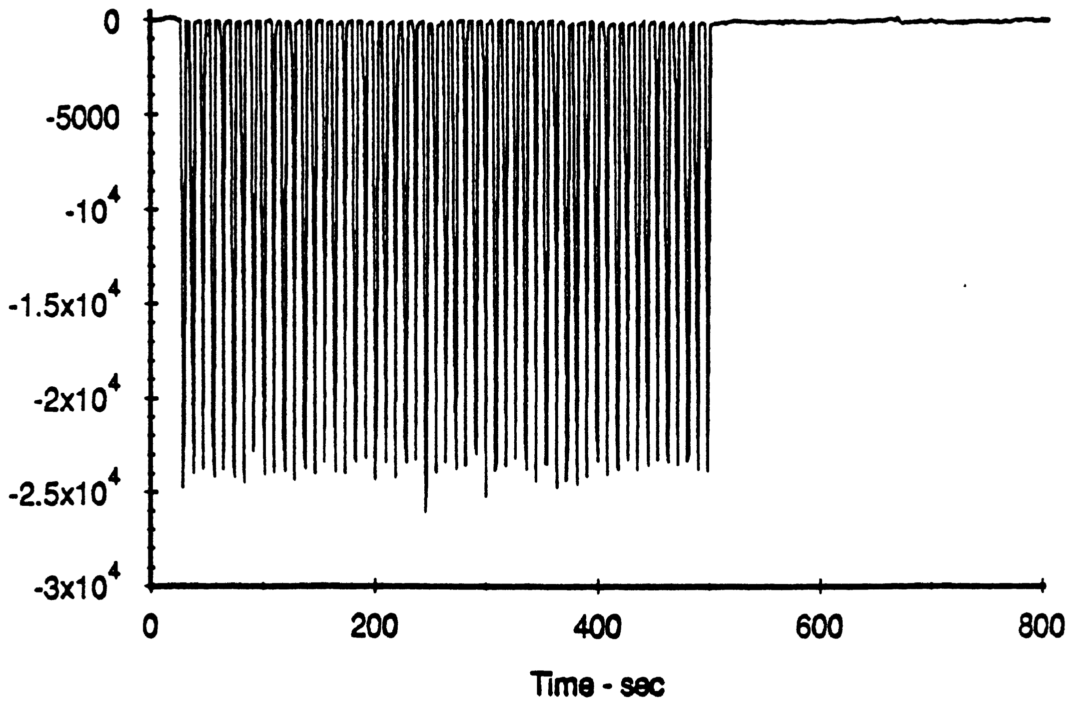


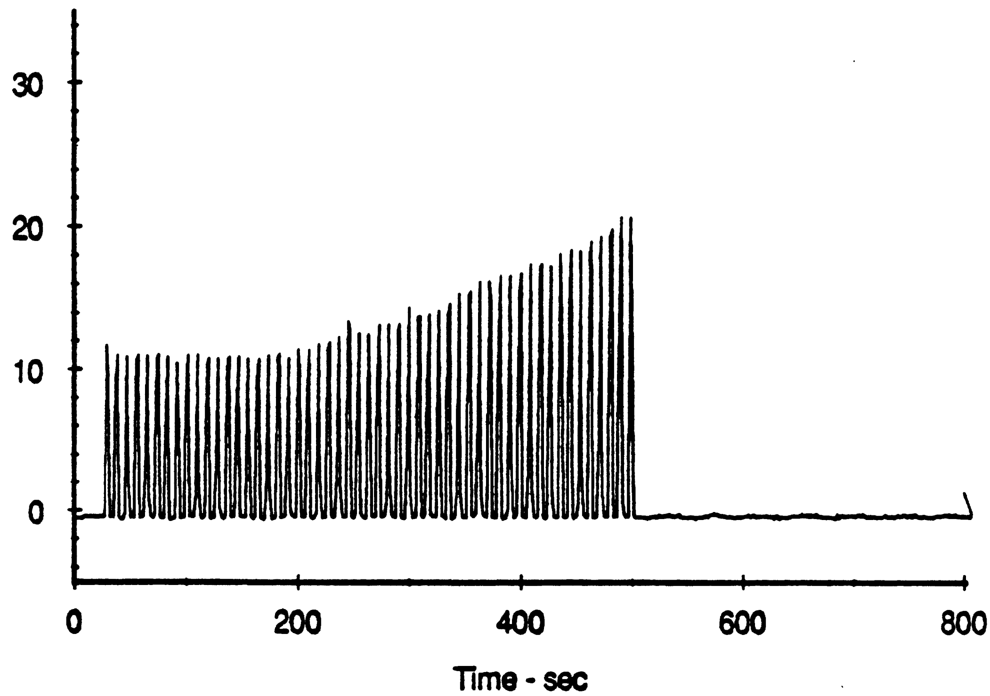
Figure 19. Cooling Rate Experiment, Snub Test

C. Brake Torque - IN-LBS



Type A Liners; Pulsed Brakes; Test ID 38; TB; no filter

D. Brake Line Pressure - PSI



Type A Liners; Pulsed Brakes; Test ID 38; BLP; no filter

Figure 19. Cooling Rate Experiment, Snub Test (continued)

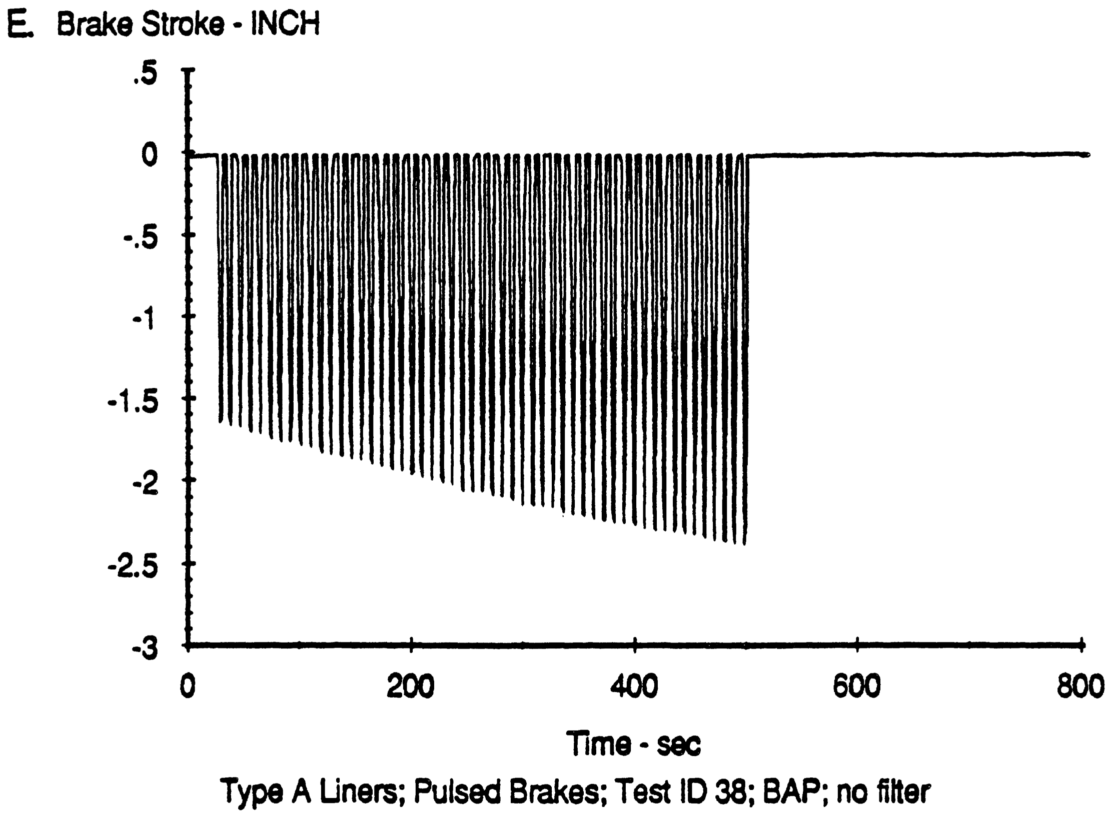


Figure 19. Cooling Rate Experiment, Snub Test (continued)

Table 6. Mobile Dynamometer Cooling Rate Experiments, 30 mph

DRAG:							
Filename	TH_f	TH_i	t_f	t_i	Energy	IntTH	H_{30}
	^oF	^oF	sec.	sec.	ft lb	^oF sec.	ft lb/ ^oF sec.
33	627.68	157.98	375.83	24.67	5929030	138588	11.15
35	637.16	159.46	436.50	32.17	6541670	166193	13.18
37	626.82	162.81	423.00	37.33	6449710	156415	14.41
39	623.58	146.62	417.67	27.50	6394450	157644	12.85
SNUB:							
Filename	TH_f	TH_i	t_f	t_i	Energy	IntTH	H_{30}
	^oF	^oF	sec	sec	ft lb	^oF sec	ft lb/ ^oF sec
34	624.84	146.03	486.33	31.17	6943850	186474	14.37
36	620.63	149.68	505.17	23.67	7221280	194607	16.09
38	617.47	146.75	500.50	27.33	6826610	190231	13.91
40*	607.14	142.16	522.00	30.67	7243100	193802	16.79

* This was taken from one thermocouple.

TH_f — Final temperature, ^oF
TH_i — Initial temperature, ^oF
t_f — Final time (braking ends), sec
t_i — Initial time (braking starts), sec
Energy — Total work done by the brake, ft lb
IntTH — Integral of brake temperature from t_i to t_f, ^oF sec
H_{30} — Cooling rate at 30 mph, ft lb/ ^oF sec

Conditions used in analysis:

TH_a — ambient temperature: 80 ^oF

m — weight of heated mass: 100 lb

cp — Specific heat: 100 ft lb/ lb ^oF

$$H = \left[\frac{\text{Energy} - mcp(TH_f - TH_i)}{\int_{t_i}^{t_f} TH\,dt - TH_a\,(t_f - t_i)}\right]$$

Cooling rates at 30 mph:

H_{30}, drag average: 12.9 ft lb/ lb $^\circ$F

H_{30}, snub average: 15.3 ft lb/ lb $^\circ$F (14.8 without file 40)

Examination of the results in Table 6 indicates that the estimated cooling rate for the pulsing strategy was $\frac{15.3 \text{ ft lb}}{^\circ\text{F sec}}$ compared to $\frac{12.9 \text{ ft lb}}{^\circ\text{F sec}}$ for the dragging strategy.

According to these results, at the same average rate of doing work, it will take longer for the brake to heat up using the snubbing strategy than it does using a dragging strategy. However, the difference in cooling rate is not large. (It is approximately 15 percent larger for the snubbing strategy.) The difference in cooling rate might appear to be large enough to cause observable differences in temperature in practice, but it did not appear to be an important factor in the downhill tests. In practice on an actual vehicle with several brakes with various levels of proportioning and effectiveness, the cooling advantages of pulsing the brakes were not large enough to be noticed.

4.2 Martensite and drum discolorization.

The mobile dynamometer was also used to simulate descending a short mountain (one mile downgrade) for one minute at 60 mph. Both pulsing (snubbing) and dragging strategies were used at an average torque level of 5,300 in lb. In the snubbing case, the duty cycle consisted of 3 sec of brake application at 15,900 in lb followed by 6 sec of no braking. In the dragging case, a constant torque level of 5,300 in lb was maintained. Each simulated descent was followed by 10-15 min of no braking, allowing the brake to cool rapidly.

Two types of linings designated A and B were used. The lining designated A is a very common type of lining often used as original equipment. The B was chosen because it was known to be prone to promoting martensite formation by Mr. Anderson who is an expert in drum-cracking [6]. Four drums were required for the combination of two strategies with two types of linings.

Results were obtained for one hundred repetitions of the mountain descent simulation starting with new (green) linings. In addition, results were also obtained after 150 repetitions in the worst case which was the drag strategy using the B lining.

The results are expressed in terms of the amount of rubbing surface area that showed color change due to the formation of hot spots. Figure 20 provides an idea of the information that was recorded through a careful examination of the inside surface of the brake drum. To obtain a rough comparison between the results for different test conditions (drag versus pulse and A versus B), the areas of color change were traced onto vellum and measured (See Figure 21). Based upon a rubbing surface area of 389 in^2 (250,900 mm^2), Table 7 presents results showing that after 100 simulated descents, the A/pulse case had the least martensite formation. If dragging were used instead of pulsing, the amount of discolored area increased seven times with the A lining. The B lining produced much worse results and the B/drag case was eleven times worse than the A/pulse case after 100 discolored for the B/drag case. Evidence in the literature [5] indicates that drum failure may

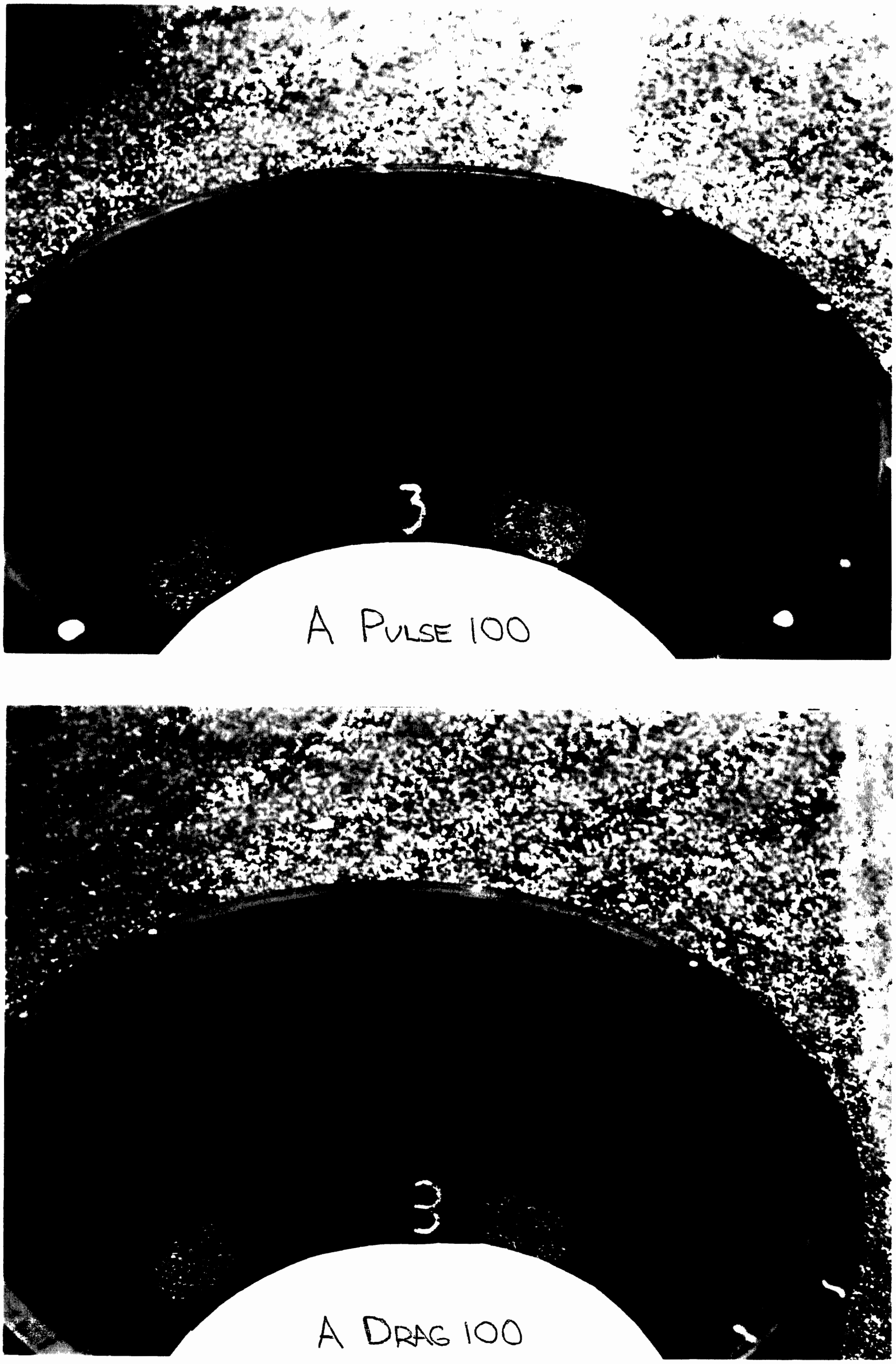


Figure 20. "3 O'clock" and "9 O'clock" Views of Brake Drums

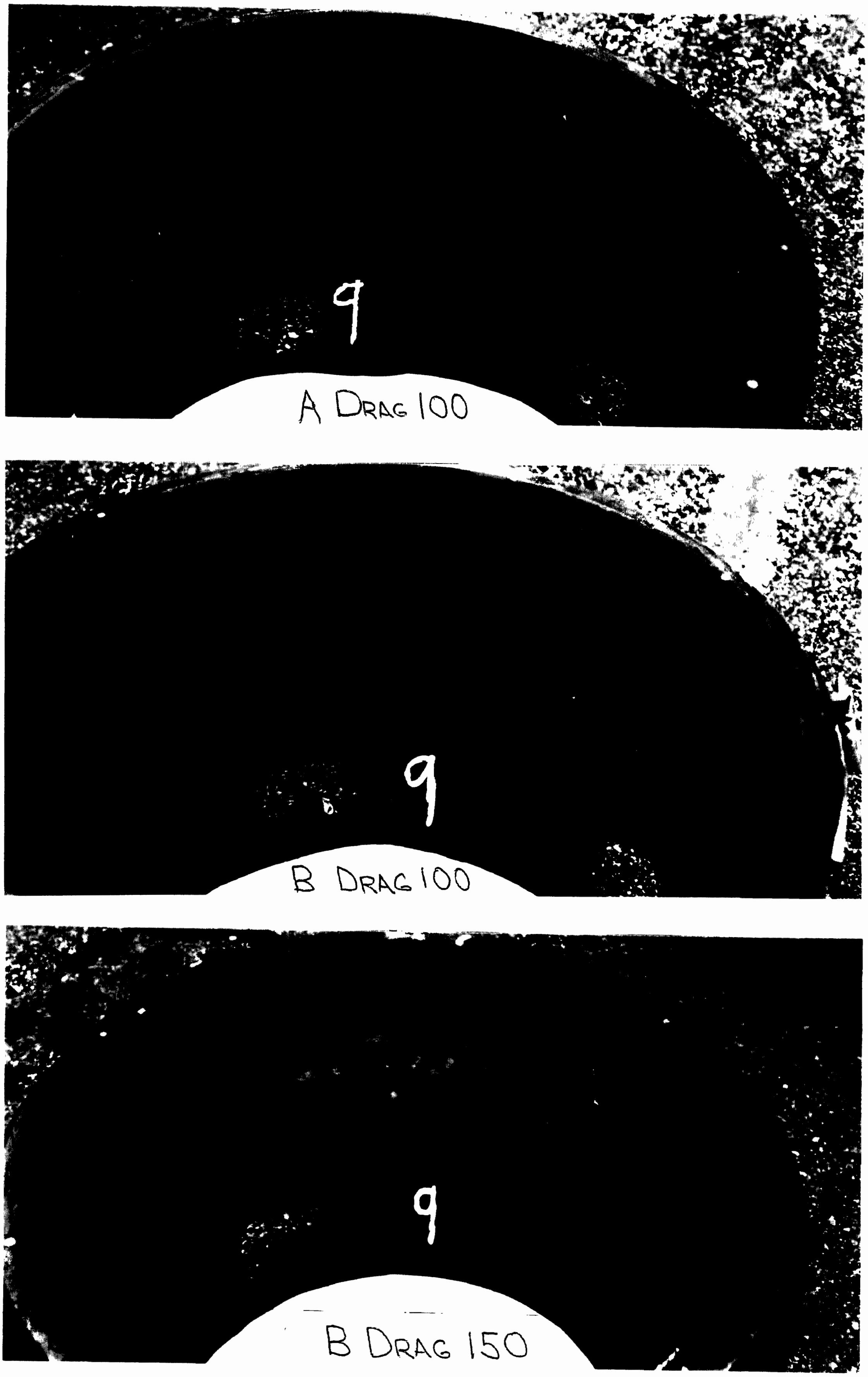


Figure 20. "3 O'clock" and "9 O'clock" Views of Brake Drums (continued)

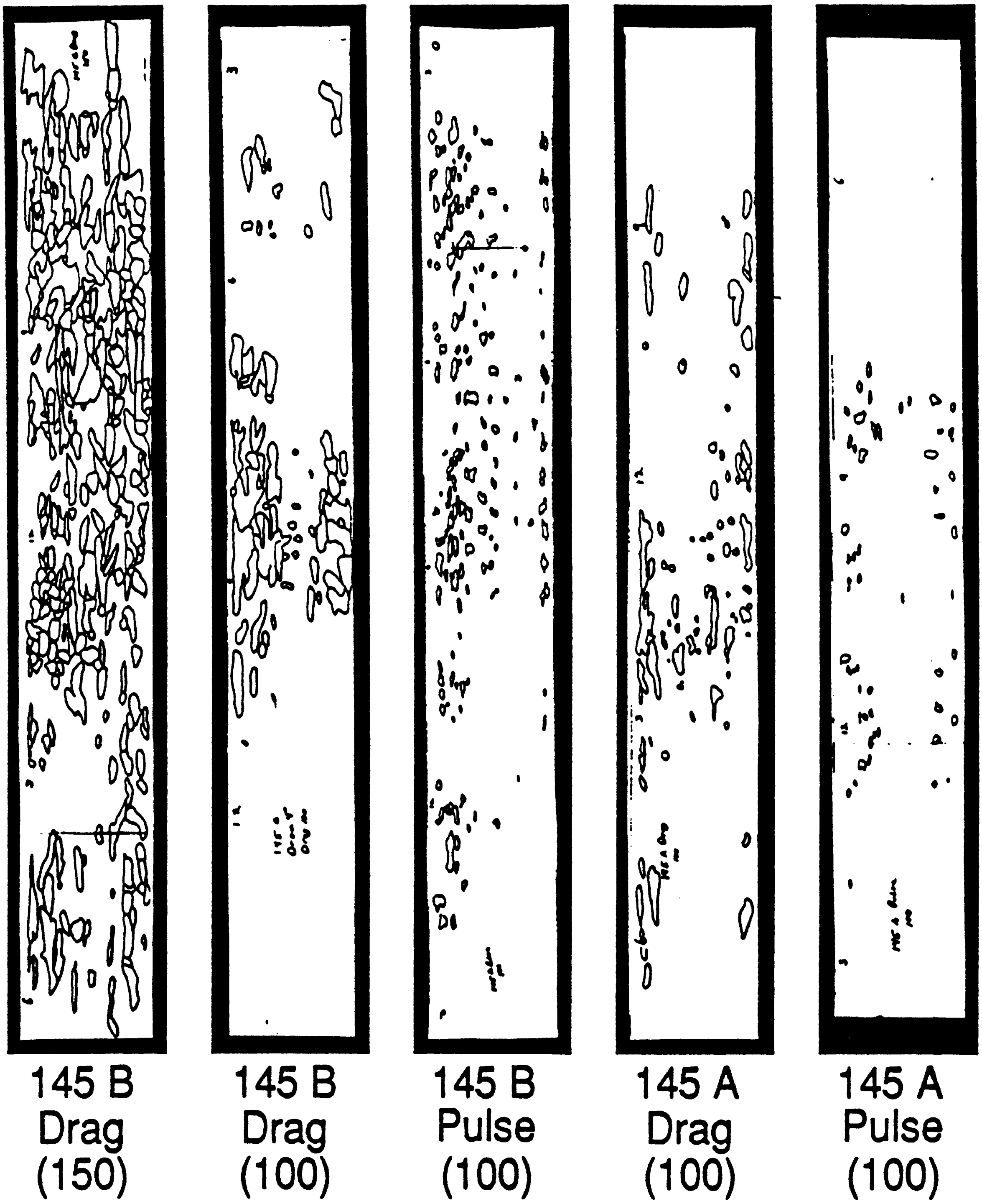


Figure 21. Tracings of Drum Discolorations Due to Hot Spots, Pulse (Snub) and Drag Tests

result soon if martensite formation continues to develop through dragging. The clear implication of these experimental results is that the snubbing strategy is much better than the dragging strategy when it comes to reducing the formation of hot spots.

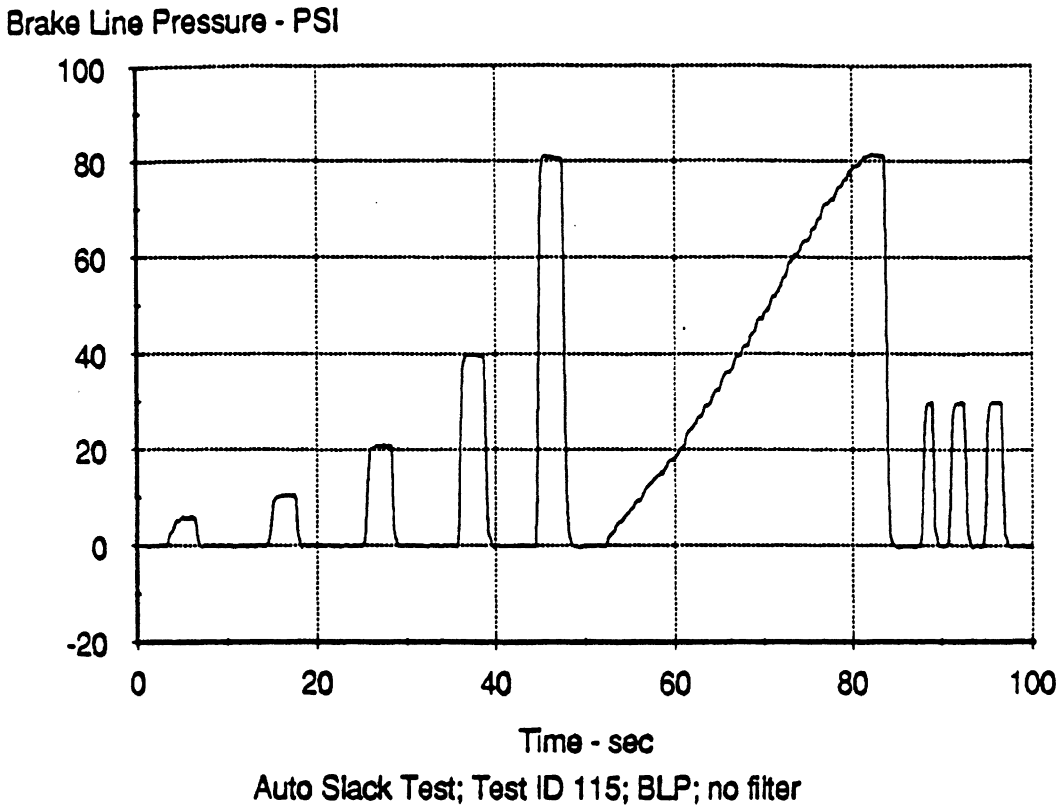
Table 7. Martensite Formation/Drum Discoloration

Number of Simulated Descents	Case	Discoloration (mm^2)	% rubbing surface area
100	A/pulse	1,880	0.8
100	B/pulse	9,840	3.9
100	A/drag	13,650	5.4
100	B/drag	21,470	8.6
150	B/drag	74,840	29.8

4.3 The influence of pulsing on an automatic slack adjuster.

There has been concern that automatic slack adjusters might overadjust when a pulsing strategy is used with hot brakes. After the brake cools, the brake would drag if it had been overadjusted. This subsection presents data showing how one common type of automatic slack adjuster (a force sensitive type) performs during repeated brake applications involving the snubbing strategy.

The automatic slack adjuster was set to start with an initial adjustment of 2 inches of stroke at 80 psi brake pressure. (The characteristics of stroke versus pressure for the initial state of the brake/slack adjuster combination are shown at 5, 10, 20, 40, and 80 psi along with a gradual "sweep" of pressure from 0 to 80 psi in Figure 22.) This initial state of adjustment is at the readjustment point according to Federal Motor Carrier Safety Standards (that is where brake penalties for out of adjustment begin). Given this state of adjustment, the automatic slack adjuster is expected to reduce the stroke at 80 psi.



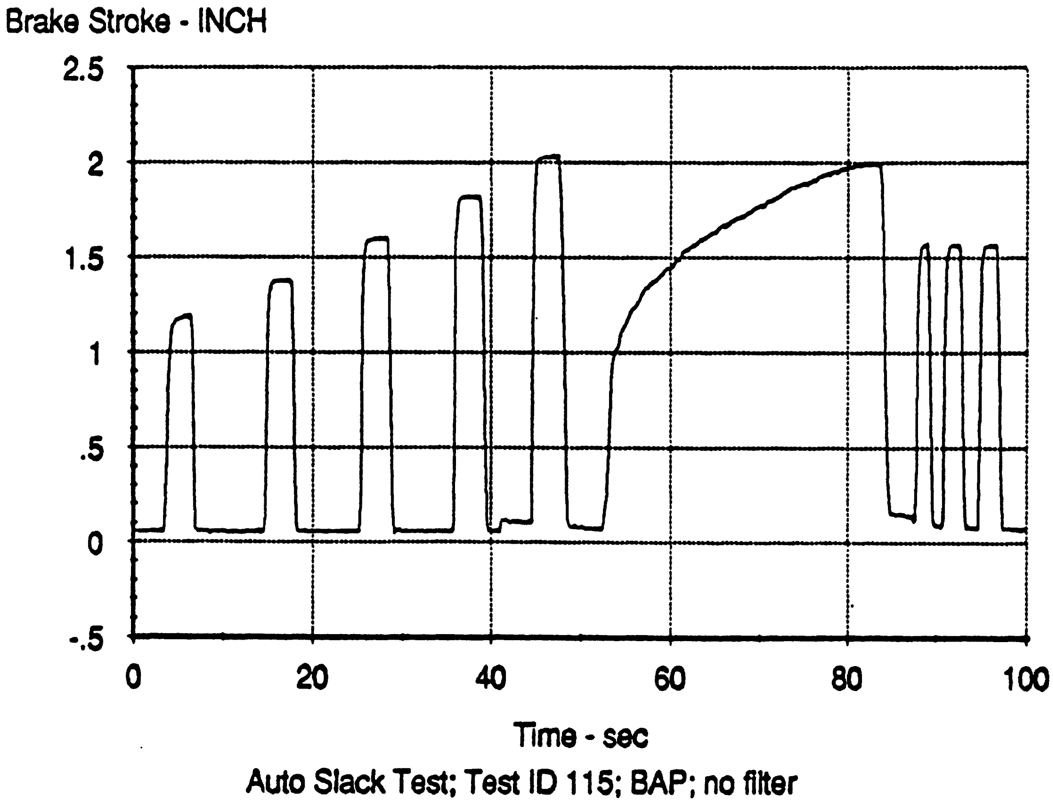
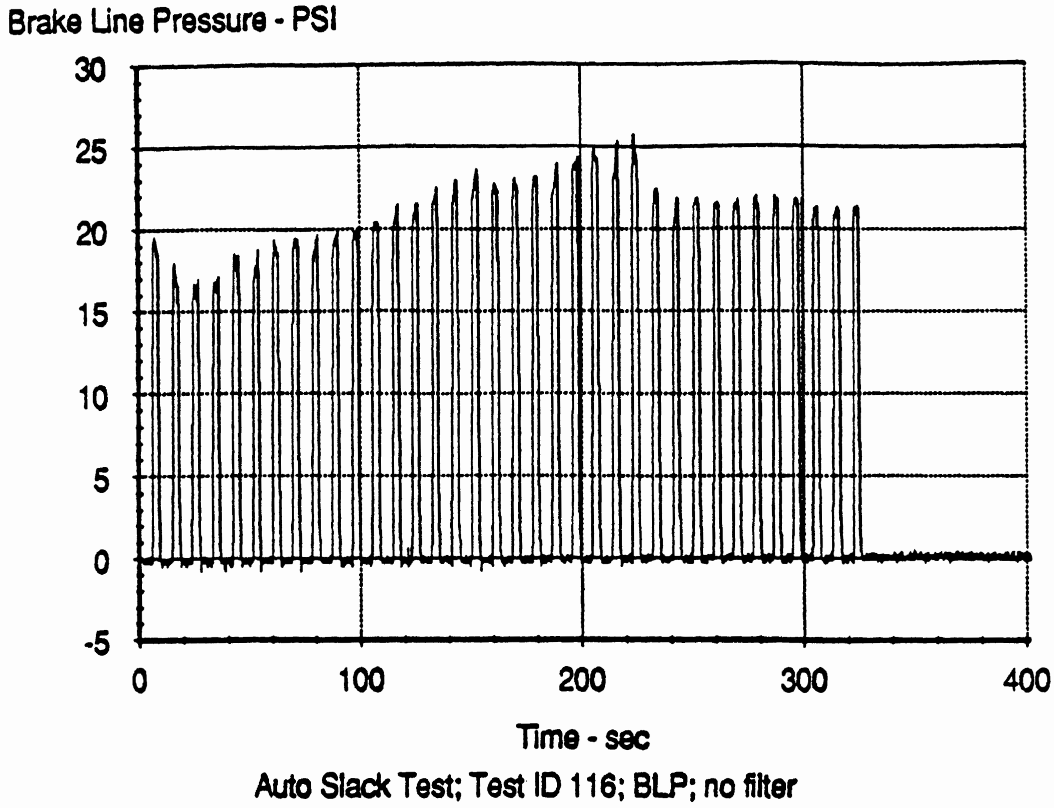


Figure 22. Pressure and Stroke for First Auto Slack Test

After a simulated mountain descent at 40 mph and of sufficient duration for the average drum temperature to exceed 600° F (this involved 36 snubs at approximately 25,000 in lb, see Figure 23), the cold stroke at 80 psi measured 1.75 in. After performing another similar mountain descent, the cold stroke at 80 psi measured 1.6 in. After a third descent, the cold stroke did not change from that attained after the second simulated mountain descent, 1.6 in. Figure 24 shows the stroke versus pressure data after the third descent, and comparison of these data with those presented in Figure 22 shows that the automatic slack adjuster is performing as it should. The snubbing strategy and the high temperatures involved did not adversely affect the performance of the automatic slack adjuster.



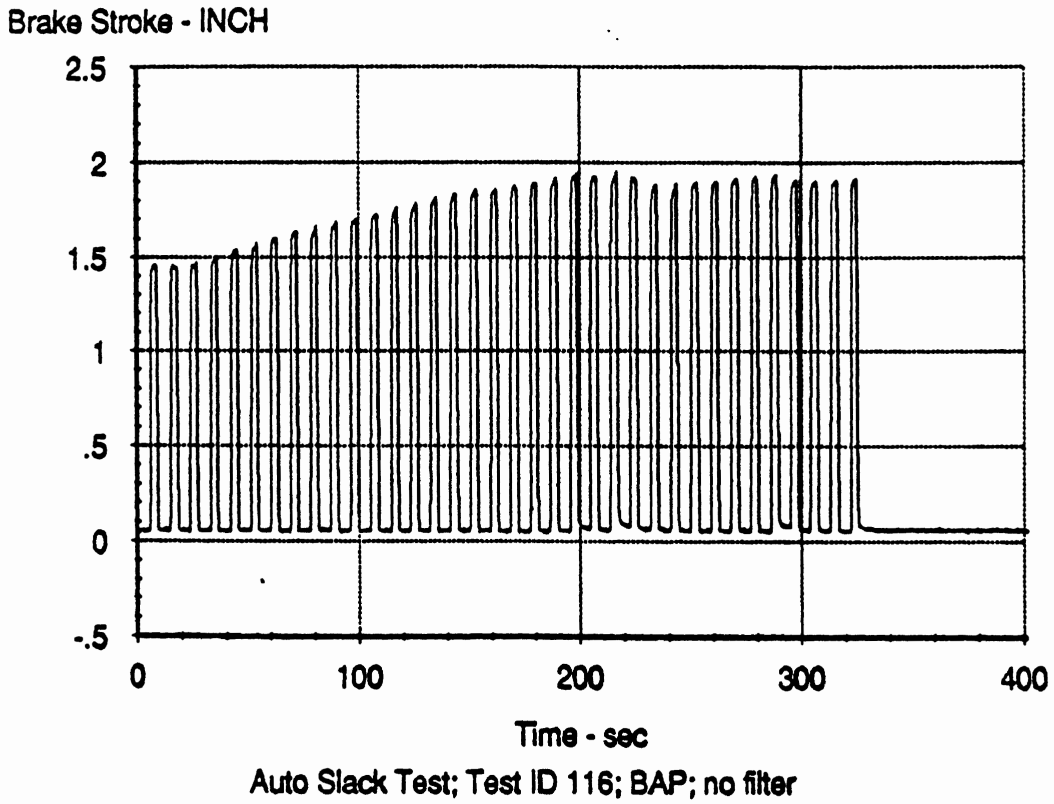


Figure 23. Simulated Mountain Descent for Auto Slack Testing

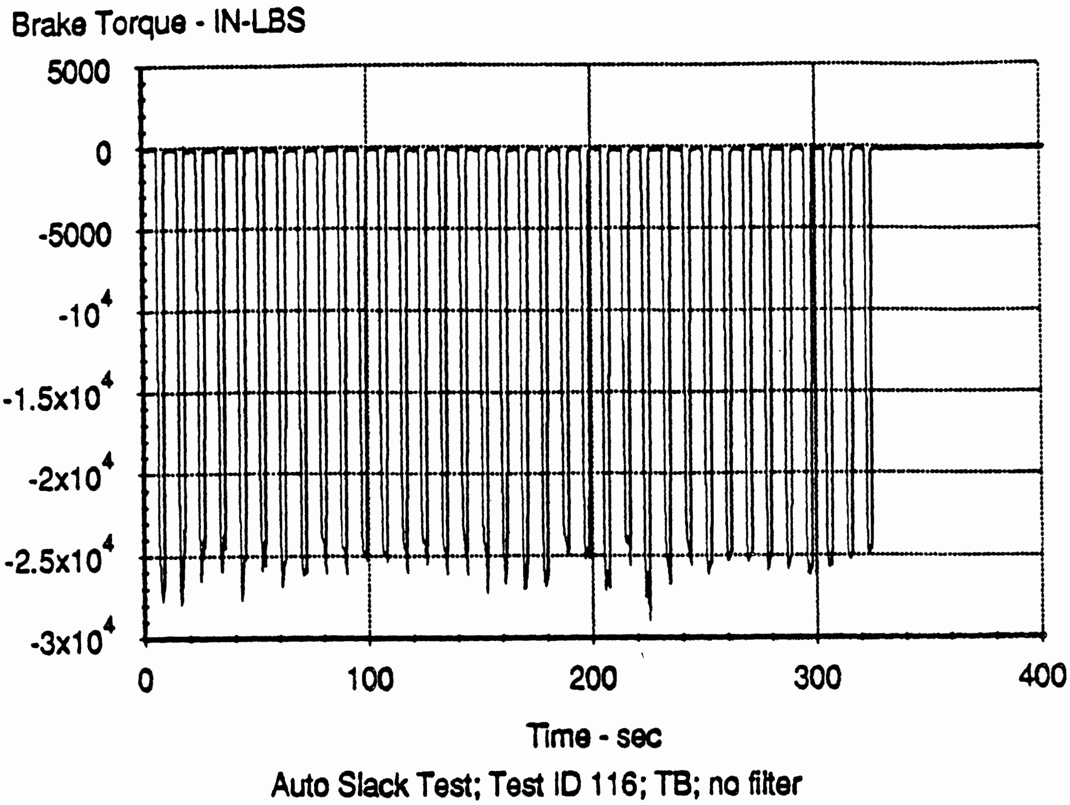
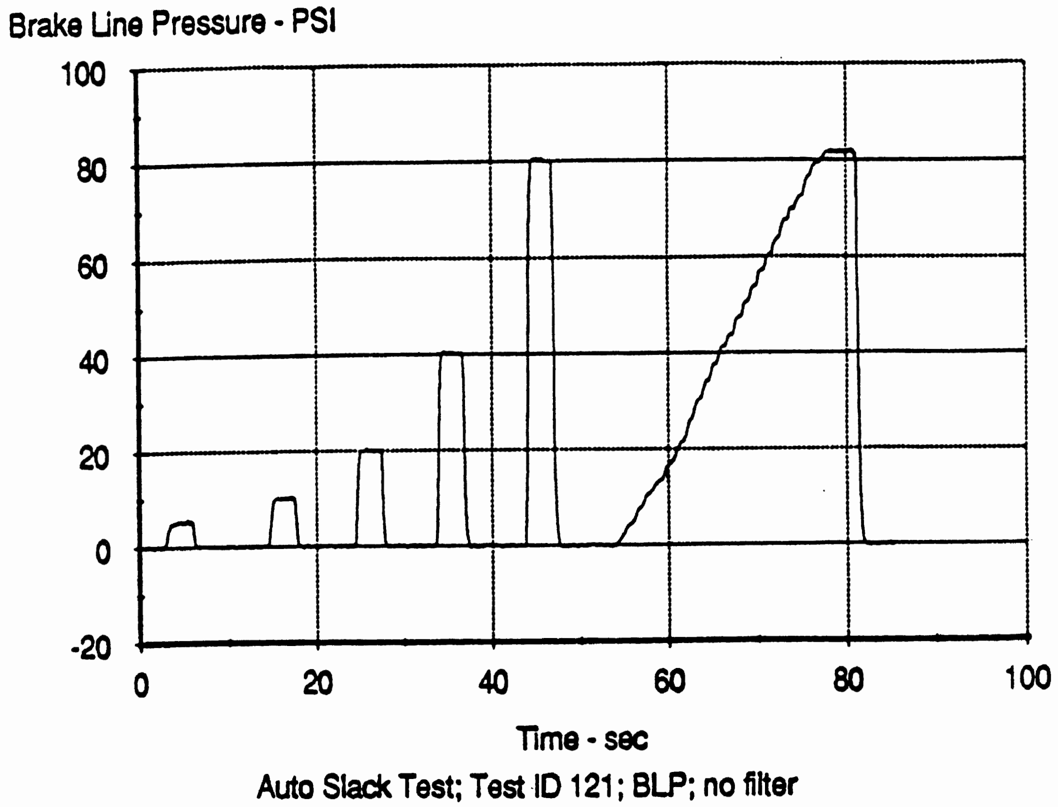


Figure 23. Simulated Mountain Descent for Auto Slack Testing (continued)



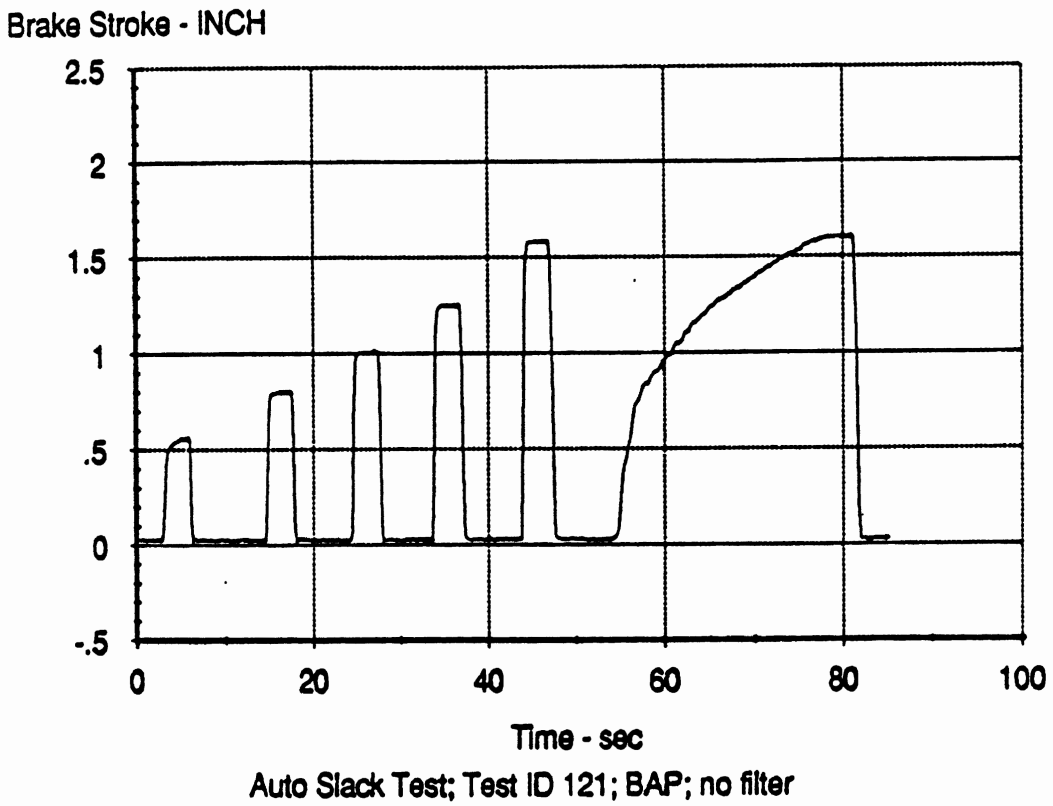


Figure 24. Stroke and Pressure After the Third "Descent"

5.0 SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS.

The findings from the mobile dynamometer experiments, described in Section 4, indicate the following:

- The snubbing (pulsing) strategy provides a higher cooling rate than that provided by the dragging strategy. However, the difference is not large.
- The dragging strategy is more conducive to the formation of hot spots than the snubbing strategy when new linings are installed.
- The use of a snubbing strategy for mountain descents will not cause a common type of automatic slack adjuster to perform improperly.

These findings all support the use of the snubbing strategy. The findings from the mountain descent testing , described in Section 3, indicate the following:

- The overall level of brake temperature per pound of brake drum will be nearly the same regardless of whether a constant dragging or a snubbing/pulsing strategy is used. The test data did not indicate that one strategy provided significantly better cooling than the other.
- The snubbing strategy involves higher pressures than the dragging strategy and thereby tends to provide a more uniform temperature distribution from brake to brake and from axle to axle. Through this mechanism, the snubbing strategy aids in making each brake do its fair share of the work even if there is a gross pneumatic imbalance.
- Very high brake temperatures result if some brakes are not doing much work. Tractors and trailers need to be matched through pressure and temperature balances if high temperatures are to be avoided in mountain descents. (The grade severity rating system is not conservative in this respect since it lumps all of the brakes together as if each brake were doing approximately a fair share of the work.)
- Significant losses in stopping capability can be attributed to misadjustment combined with pneumatic imbalance. Particularly poor stopping performance will occur after mountain descents when the tractor's brakes are misadjusted and the trailer's brakes are very hot due to pneumatic imbalance, or vice versa with hot tractor brakes due to pneumatic imbalance and the trailer's brakes misadjusted.
- In some circumstances, with combined misadjustment and imbalance, the snubbing strategy has been found to lead to hotter brakes for the misadjusted brakes, which in turn leads to an additional increment in stopping distance after a mountain descent.

The findings from the mountain descent tests favor the snubbing strategy in that the hottest brake will be cooler if snubbing is used rather than dragging. However, the differences in average brake temperature are not large enough or consistent enough to favor either strategy. The snubbing strategy appears to have an advantage over the dragging strategy because the snubbing strategy causes each brake to come closer to doing its fair share of the work, particularly if there is a pressure imbalance at low brake pressure.

It is interesting to observe that a pressure imbalance can result in a situation that warns the driver that the brakes are overheating. If the brakes are imbalanced and the driver is proceeding at too high of a speed, the brakes doing more than their fair share of the work will heat up first. If the driver sees smoke or smells these hot brakes, the driver can use the other brakes (the ones that have not overheated) to stop the vehicle safely.

This situation was observed in practice many times on the mountain on I-64. The highway has broad shoulders. On many runs down the mountain with the test vehicle, other heavy trucks with one set of smoking brakes were seen stopped on the shoulder. The drivers had apparently learned that they did not need to pull into the runoff ramps and get stuck. (The mountain has two runoff ramps, one at the middle and one at the bottom. The one in the middle has been used about once a week since it was built.) The drivers chose to pull over, stop, and wait on the shoulder for about 40 min for their brakes to cool.

There is a danger that a tire might explode at the bead due to the nature of the heat flow while the vehicle is stopped. This is a particularly dangerous situation in that it may take about 10 min for the wheel to explode after the vehicle has stopped. The driver should stay clear of the wheels with hot brakes.

The point to be made is that there may be circumstances in which some brakes overheat and the other brakes can easily stop the vehicle. This situation can be used as a safety warning if the road has plenty of shoulder room to stop in. However, there is a significant loss of time while waiting for the brakes to cool. Nevertheless, drivers of vehicles with some (but not all) brakes overheated should stop to let the brakes cool before proceeding.

With regard to instructions in the Commercial Drivers License Manual, the results of this study do not show that dragging is superior to pulsing. With respect to the overall average temperature, the results indicate that either strategy is as good as the other. For a given vehicle on a particular mountain, the total heat retained by the brakes after descending the mountain will be nearly the same regardless of whether a pulsing or dragging strategy is used. The important issue is to use a control speed that is appropriate for the slope of the downgrade, the length of the downgrade, the weight of the vehicle, and the balance of the braking system.

A snubbing strategy that allows for approximately ±3 mph speed variation about the control speed has been found to be reasonable and practical. The owners and operators of commercial vehicles should be made aware that the snubbing strategy will produce more uniform temperatures throughout the vehicle, thereby leading to less brake wear overall and less frequent need for readjustment and relining. They should also be made aware that after mountain descents misadjustment on one set of brakes can lead to long stopping distances, particularly if the brake system has a large pressure imbalance tending to reduce the work done by the misadjusted brakes.

Although the snubbing strategy has been found to have advantages over the dragging strategy, the main conclusion from this investigation of downhill braking is that heavy trucks should proceed down the mountain at a speed (a controlled speed) that will be low enough to prevent the brakes from overheating regardless of the braking strategy employed. Given that a prudent control speed is used by the driver, the benefits of a snubbing strategy can be safely attained. These conclusions support the recommended wording of advice for commercial vehicle drivers as presented in Section 1 of this report. Specifically, that advice is to go slowly in the proper gear and remember that a snubbing strategy can aid in (a) making each brake do its fair share of the work and (b) reducing the tendency for hot-spotting of brake drums.

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2. The University of Michigan Transportation Research Institute, *Simplified Models of Truck Braking and Handling: A User's Manual for the Brake Temperature Model,* April 1990.
3. University of Michigan College of Engineering, *Mechanics of Heavy Duty Trucks and Truck Combinations*, Chapters 10 and 18, July 8-12, 1991.
4. Myers, T.T., et al. *Feasibility of a Grade Severity Rating System*, Final Report, Contract No. DOT-FH-11-9253, Systems Technology, Inc., August 1979.
5. Bowman, B. *Grade Severity Rating System (GSRS)—User's Manual,* NTIS, Report No. FHWA-1P-88-015, May 1988.
6. Anderson, A.E., Knapp, R.A. "Hot Spotting in Automotive Friction Systems." *Wear* 135, 319-337, 1990.

APPENDIX A
PREDICTIONS OF BRAKE TEMPERATURES

UMTRI MODEL FOR PREDICTING BRAKE TEMPERATURES

The predictions of brake temperature presented here were made using a simplified model [2] of the heat flow into the brakes of a heavy vehicle descending a mountain and/or changing velocity. The model is based upon the simplified theory presented in Appendix D. It allows the total braking effort to be proportioned among the various brakes so that the temperature of each brake can be computed.

The computer program, which is based on the model, uses input data describing the mountain and the vehicle's speed profile; the vehicle's weight, aerodynamic properties, and rolling resistance; and thermodynamic properties of the brakes, the proportioning of braking effort between brakes, and the cooling rates of the brakes. (See Figure A1.)

EXAMPLE PREDICTION: UMTRI TRUCK

An example representing a dragging run is presented in Figure A1. This figure contains a listing of the input data and graphical results for selected brakes.

In the project, these types of calculations were used in planning the tests and to see if the test results seemed reasonable at the time they were being obtained at the mountain in West Virginia. (The program runs on personal computers. It can be easily used in the field.)

Although a velocity profile representative of the snubbing strategy could be input to the program, the resulting temperatures would be nearly the same unless the cooling coefficients were changed. If the cooling coefficients are changed, it should be obvious that the temperatures will change accordingly. Examination of the example predictions indicates that the test results are in agreement with the theoretical understanding represented by the model.

EXAMPLE PREDICTION: NHTSA TRACTOR SEMITRAILER (3-S2)

An example, representing a dragging run of the 3-S2, is presented in Figure A2. This figure contains a listing of the input data and graphical results for selected brakes of the NHTSA vehicle.

Examination of the results indicate that the brakes on the NHTSA vehicle are predicted to become much hotter than the temperatures predicted for the UMTRI truck. At first this seemed surprising because the amount of vehicle mass per pound of brake mass is nearly equal between the two vehicles. However the NHTSA vehicle is much more fuel efficient in terms of less drag. In addition, the proportioning of braking effort on the NHTSA vehicle is quite imbalanced with the trailer brakes doing more than their fair share of the work. Furthermore the cooling rate of the brakes on the NHTSA vehicle is much less than that of the UMTRI truck. All of these factors combined to elevate the temperature of the hottest brake on the NHTSA vehicle. The brake imbalance was particularly damaging in this respect.

TEMP-1	Left front brake
TEMP-2	Right front brake
TEMP-3	Left brake on the front drive axle

BRAKE TEMPERATURE

FILE NAME:C:SND36AX3.BKT

Vehicle Parameters

Total Weight = 46420.00 lbs
Frontal Area = 100.00 ft^2
Total Number of Axles = 3
Type of Tires: Bias Ply

Road and Ambient Parameters

Ambient Temperature = 90.00 F
Air Drag Coefficient = .8500
Road Surface Coefficient = 1.2000
Number of Points in Road Profile = 17
Number of Points in Aux. Retarding Power Table = 2
Number of Stops = 0

Auxiliary Retarding Power Table

Velocity (mph)	Retarding Power (hp)
.00	.0000
36.00	64.0000

Brake Parameters

Axle	Brake	Initial Brake Temperature (F)	Brake Drum Weight (lbs)	Specific Heat Cp (hp-hr)/(lbs-F)
1	1	100.00	67.00	.500E-04
	2	100.00	67.00	.500E-04
2	3	100.00	97.00	.500E-04
	4	100.00	97.00	.500E-04
3	5	100.00	97.00	.500E-04
	6	100.00	97.00	.500E-04

Brake Parameters (Cont.)

Axle	Brake	Cooling Coefficients K1 (hp/F)	K2 (hp/F-mph)	Proportioning
1	1	.0100	.000293	.0950
	2	.0100	.000293	.1050
2	3	.0140	.000600	.2000
	4	.0140	.000600	.2000
3	5	.0140	.000600	.2000
	6	.0140	.000600	.2000

Road Profile

Distance (Miles)	Elevation (Ft)	Speed (MPH)
.000	2765.35	36.00
.189	2751.59	36.00
.379	2708.23	36.00
.454	2682.60	36.00
.568	2640.60	36.00
1.326	2360.00	36.00
1.515	2295.00	36.00
2.178	2084.50	36.00
2.27[illegible]	2050.00	36.00
2.746	1875.40	36.00
2.841	1843.99	36.00
3.599	1596.96	36.00
3.636	1586.91	36.00
4.659	1344.01	36.00
4.735	1330.08	36.00
4.848	1324.71	36.00
5.038	1331.31	36.00

Stop Times

Time (Minutes)

Figure A.1. Parametric Data and Predicted Brake Temperatures as a Function of Distance Down the Mountain for the UMTRI Truck

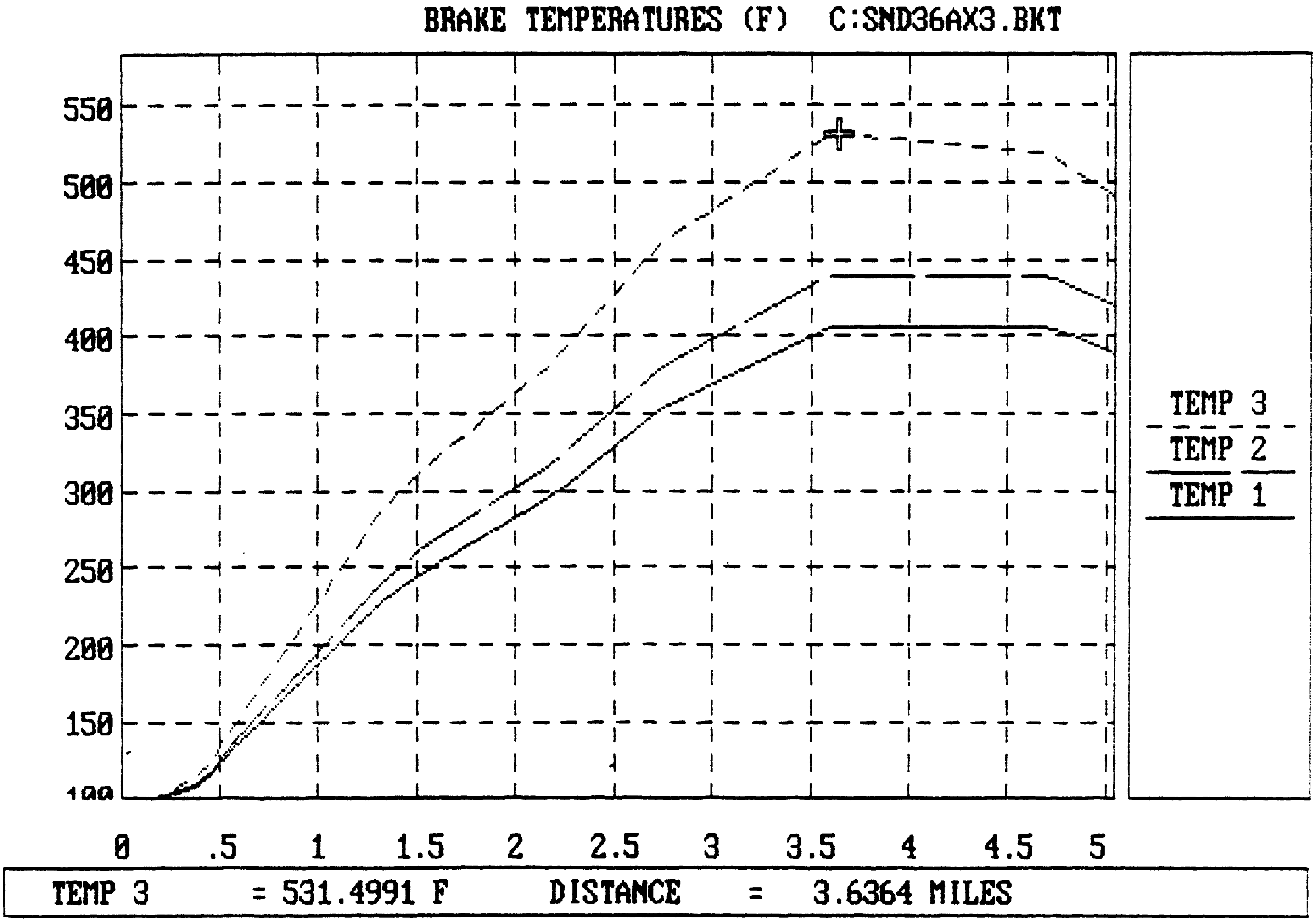


Figure A.1. Parametric Data and Predicted Brake Temperatures as a Function of Distance Down the Mountain for the UMTRI Truck (continued)

TEMP-1	Left front brake
TEMP-4	Right brake on the front drive axle
TEMP-7	Left brake on the front trailer axle
TEMP-8	Right brake on the front trailer axle

BRAKE TEMPERATURE

FILE NAME:C:SANDMF20.BKT

Vehicle Parameters

Total Weight = 80000.00 lbs
Frontal Area = 80.00 ft^2
Total Number of Axles = 5
Type of Tires: Radials

Road and Ambient Parameters

Ambient Temperature = 90.00 F
Air Drag Coefficient = .7500
Road Surface Coefficient = .7500
Number of Points in Road Profile = 17
Number of Points in Aux. Retarding Power Table = 2
Number of Stops = 0

Auxiliary Retarding Power Table

Velocity (mph)	Retarding Power (hp)
.00	.0000
30.00	44.0000

Brake Parameters

Axle	Brake	Initial Brake Temperature (F)	Brake Drum Weight (lbs)	Specific Heat Cp (hp-hr)/(lbs-F)
1	1	100.00	65.00	.500E-04
	2	100.00	65.00	.500E-04
2	3	100.00	105.00	.500E-04
	4	100.00	105.00	.500E-04
3	5	100.00	105.00	.500E-04
	6	100.00	105.00	.500E-04
4	7	100.00	105.00	.503E-04
	8	100.00	105.00	.500E-04
5	9	100.00	105.00	.500E-04
	10	100.00	105.00	.500E-04

Brake Parameters (Cont.)

Axle	Brake	Cooling Coefficients K1 (hp/F)	Cooling Coefficients K2 (hp/F-mph)	Proportioning
1	1	.0042	.000450	.0460
	2	.0042	.000450	.0650
2	3	.0064	.000700	.0830
	4	.0064	.000700	.0930
3	5	.0064	.000700	.0830
	6	.0064	.000700	.0930
4	7	.0064	.000700	.1300
	8	.0064	.000700	.1560
5	9	.0064	.000700	.1210
	10	.0064	.000700	.1300

Road Profile

Distance (Miles)	Elevation (Ft)	Speed (MPH)
.000	2765.35	20.00
.189	2751.59	20.00
.379	2708.23	20.00
.454	2682.60	20.00
.568	2640.60	20.00
1.326	2360.00	20.00
1.515	2295.00	20.00
2.178	2084.50	20.00
2.273	2050.00	20.00
2.746	1875.40	20.00
2.841	1843.99	20.00
3.599	1596.96	20.00
3.636	1586.91	20.00
4.659	1344.01	20.00
4.735	1330.08	20.00
4.848	1324.71	20.00
5.038	1331.31	20.00

Figure A.2. Parametric Data and Predicted Brake Temperatures as a Function of Distance Down the Mountain for the NHTSA 3-S2

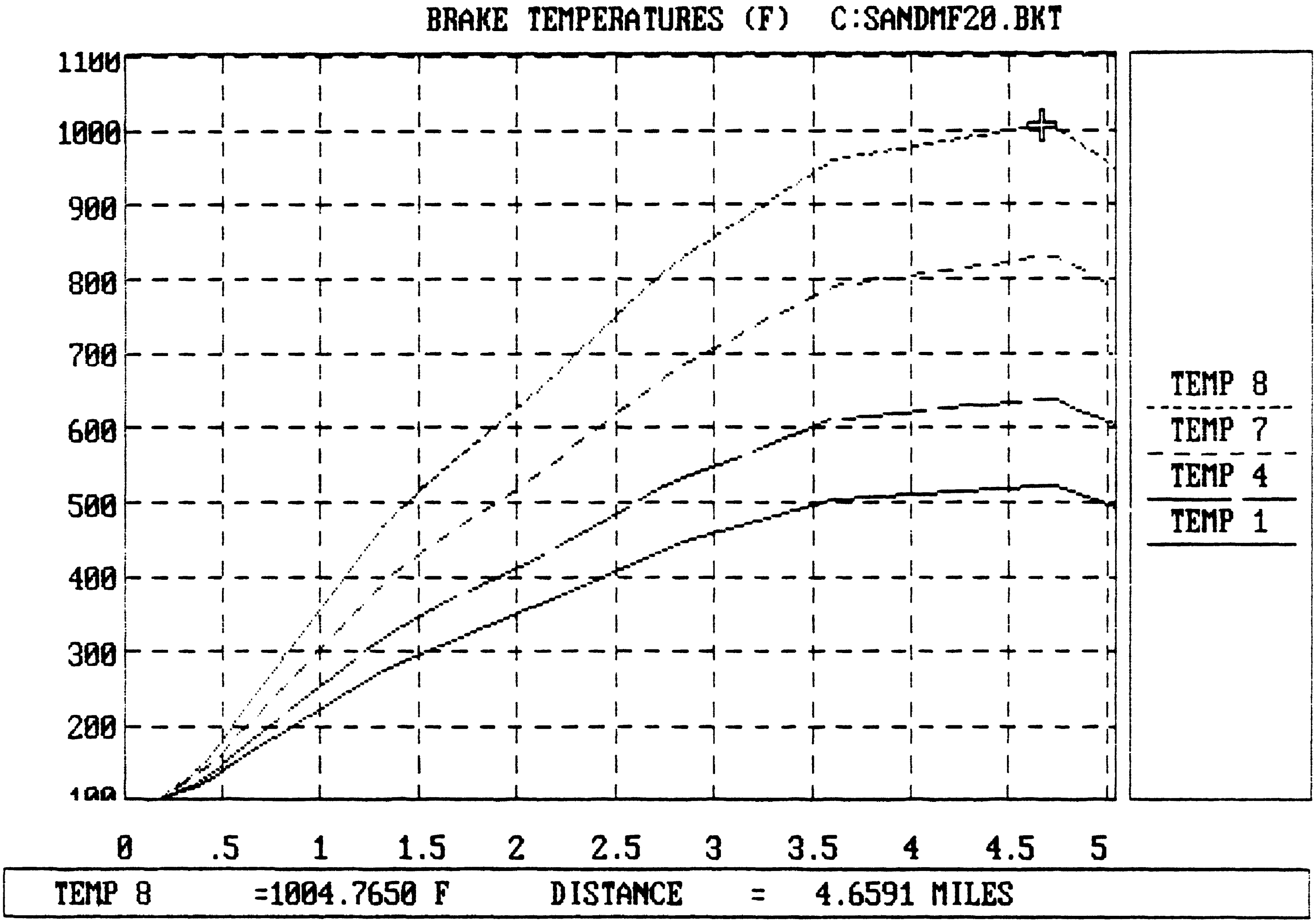


Figure A.2. Parametric Data and Predicted Brake Temperatures as a Function of Distance Down the Mountain for the NHTSA 3-S2 (continued)

APPENDIX B
INSTRUMENTATION

UMTRI TRUCK

Data Collection System

The analog signals were filtered at 3Hz and then sampled at 6Hz with a digital data acquisition system. The data was then stored on disk in the ERD file format.

Downhill Test Truck

The vehicle velocity was measured with a DC tachometer type fifth wheel. Brake line pressures were measured at five locations using strain-gauge-type pressure transducers. The pressure transducers were located at the left brake chamber for each of the three tractor axles, and at each of the two outlets on the treadle valve. Brake stroke was measured with linear motion potentiometers at each of the six brake actuators. Brake temperatures were measured with type-K thermocouples. Three thermocouples were located in each of the six brake assemblies. Each brake assembly had two thermocouples spot welded to the outside of the drum, located on the center line 180° apart. Slip rings were used to carry the drum temperature signals to the data storage unit. Each brake assembly had one thermocouple embedded in the center of the upper pad of the liner on the leading brake shoe.

MOBILE TRUCK TIRE DYNAMOMETER

The vehicle velocity was measured with a DC-tachometer-type fifth wheel. Test wheel rotation rate was measured with a DC tachometer. Fx, Fy, and braking torque were measured with the mobile truck tire dynamometer's load cell. Brake line pressure was measured with a strain-gauge-type pressure transducer mounted at the brake chamber. Brake stroke was measured with a linear motion potentiometer at the brake actuator. Brake temperatures were measured with type-K thermocouples. The brake assembly had two thermocouples spot welded to the outside of the drum, located on the center line 180° apart. There were ten thermocouples embedded in the brake liners in the following locations: center of the upper pad on the trailing shoe, center of lower pad on the trailing shoe, center of the lower pad on the leading shoe, and a horizontal line of seven thermocouples across the center of the upper pad on the leading shoe.

NHTSA TRUCK

The instrumentation used on the NHTSA tractor semitrailer was of much the same type as that employed on the UMTRI truck. The main differences were that there were many more channels of data to record on the NHTSA vehicle since it had ten brakes. In addition the fifth wheel was outfitted for measuring stopping distance. The following table lists the quantities recorded for the downhill tests.

Table B.1 VRTC Data Channels for Downhill Tests

Name	Description
BRLT01	Brake lining temperature - left tractor front wheel
BRLT02	Brake lining temperature - right tractor front wheel
BRLT03	Brake lining temperature - left tractor intermediate wheel
BRLT04	Brake lining temperature - right tractor intermediate wheel
BRLT05	Brake lining temperature - left tractor rear wheel
BRLT06	Brake lining temperature - right tractor front wheel
BRLT07	Brake lining temperature - left trailer front wheel
BRLT08	Brake lining temperature - right trailer front wheel
BRLT09	Brake lining temperature - left trailer rear wheel
BRLT10	Brake lining temperature - right trailer rear wheel
BRDT01	Brake drum temperature - left tractor front wheel
BRDT02	Brake drum temperature - right tractor front wheel
BRDT03	Brake drum temperature - left tractor intermediate wheel
BRDT04	Brake drum temperature - right tractor intermediate wheel
BRDT05	Brake drum temperature - left tractor rear wheel
BRDT06	Brake drum temperature - right tractor front wheel
BRDT07	Brake drum temperature - left trailer front wheel
BRDT08	Brake drum temperature - right trailer front wheel
BRDT09	Brake drum temperature - left trailer rear wheel
BRDT10	Brake drum temperature - right trailer rear wheel
BPRD01	Brake stroke - left tractor front wheel
BPRD02	Brake stroke - right tractor front wheel
BPRD03	Brake stroke - left tractor intermediate wheel
BPRD04	Brake stroke - right tractor intermediate wheel
BPRD05	Brake stroke - left tractor rear wheel
BPRD06	Brake stroke - right tractor front wheel
BPRD07	Brake stroke - left trailer front wheel
BPRD08	Brake stroke - right trailer front wheel
BPRD09	Brake stroke - left trailer rear wheel
BPRD10	Brake stroke - right trailer rear wheel
CPRS	Control line pressure
BRSPF	Brake chamber pressure - front axle
BRSPD	Brake chamber pressure - drive axles
BRSPT	Brake chamber pressure - trailer axles
BREVNT	Brake event (brake applied)
U	Vehicle speed
DECEL	Vehicle deceleration
DISTX	Distance traveled

The downhill braking data signals were sampled at ten samples per second for the NHTSA vehicle. The sampling rate was increased to fifty samples per second during the hot stops after descending the mountain. The data were stored on disks using a format developed at VRTC by NHTSA personnel.

APPENDIX C
VEHICLE DESCRIPTIONS

UMTRI TRUCK

This section provides further data (beyond that given in Section 2) pertaining to the braking properties of the vehicle used to represent a straight truck in the downhill tests.

All six brakes had 5.5 in slack arm lengths. The front brakes had type-20 chambers and the rear brakes had type-30 chambers.

The performance of these brakes was measured on the roller dynamometer at VRTC, NHTSA's facility in East Liberty, Ohio. See Figure C1 for graphs of the results. These results provide an indication of the proportioning of the brakes.

Characteristics of the valves used in the study are quantified by the results for threshold pressure measurements per SAE Practice J1505. See Table C1.

The UMTRI vehicle took approximately 23.5 sec to coast down from 40 to 25 mph in gear 6H. (The vehicle had a 13 speed transmission (Fuller model RTO12513) and a Detroit Diesel V8 engine model 8V92-PA. The rear axle ratio was 4.11.) The coast down deceleration was approximately 0.03g in this speed range.

NHTSA TRACTOR SEMITRAILER (3-S2)

The performances of the brakes on the vehicle supplied by NHTSA are characterized by data measured on the roller dynamometer at VRTC, NHTSA's facility in East Liberty, Ohio. See Figure C2 for graphs of the results. These results provide an indication of the proportioning of the brakes.

Characteristics of the valves used in the study are quantified by the results for threshold pressure measurements per SAE Practice J1505. See Table C2.

Results of brake timing tests are presented in Table C3. (The timing was good for both vehicles.)

The NHTSA vehicle had a coast down deceleration of approximately 0.014g in gear and 0.01g in neutral at low speed.

The cooling time for a trailer brake for cooling from 700°F to 200°F was approximately 1.5 hr with the vehicle parked and 1.0 hr with the vehicle driving at 30 mph.

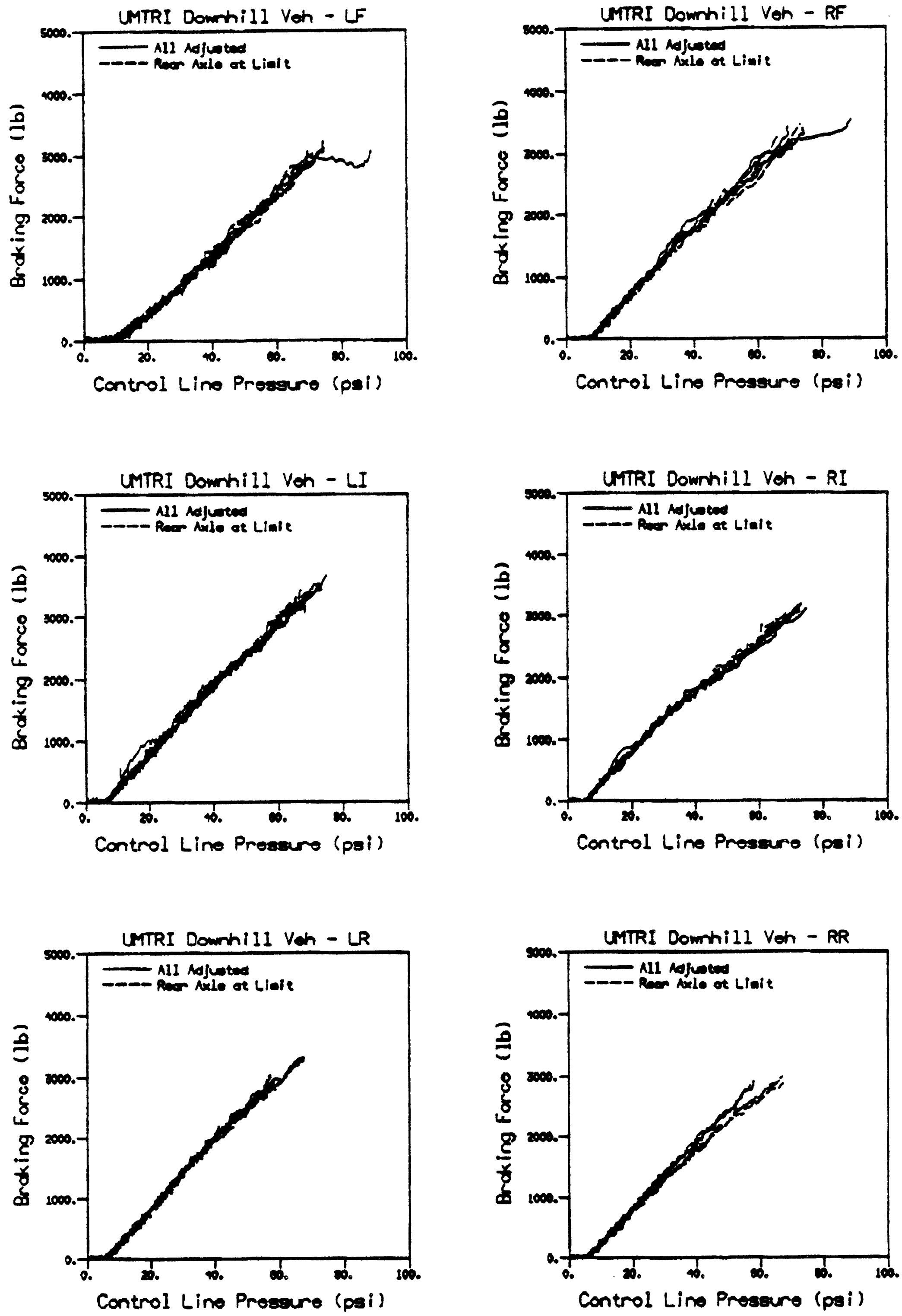


Figure C.1. Roller Dynamometer Results for the Truck

Table C.1

THRESHOLD PRESSURES - UMTRI DOWNHILL VEHICLE

	Left			Right		
	Apply	Release	Avg	Apply	Release	Avg
			Brakes Fully Adjusted			
Front						
	11.66	4.81	8.232	8.06	5.16	6.607
	11.80	5.30	8.550	7.91	3.89	5.900
	12.37	4.73	8.550	7.56	4.52	6.042
Avg	*11.94*	*4.95*	*8.444*	*7.84*	*4.52*	*6.183*
Intermediate						
	7.49	5.30	6.395	6.57	4.81	5.688
	7.07	5.30	6.183	6.92	4.88	5.900
	7.49	5.37	6.430	7.91	4.81	6.360
Avg	*7.35*	*5.32*	*6.336*	*7.13*	*4.83*	*5.983*
Rear						
	7.49	6.29	6.890	6.71	5.02	5.865
	7.63	6.36	6.996	6.22	4.24	5.229
	8.06	5.44	6.748	5.87	4.17	5.017
Avg	*7.73*	*6.03*	*6.878*	*6.27*	*4.48*	*5.370*
			Rear Axle at Recommended Limit			
Front						
	12.86	5.65	9.257	8.69	4.31	6.501
	13.07	5.09	9.080	8.48	4.45	6.466
	11.52	4.73	8.126	8.69	4.03	6.360
Avg	*12.48*	*5.16*	*8.821*	*8.62*	*4.26*	*6.442*
Intermediate						
	8.69	5.02	6.854	7.00	4.88	5.936
	7.56	5.30	6.430	6.92	4.81	5.865
	8.13	5.58	6.854	7.21	5.51	6.360
Avg	*8.13*	*5.30*	*6.713*	*7.04*	*5.07*	*6.054*
Rear						
	8.27	6.22	7.243	6.78	5.16	5.971
	7.00	5.65	6.324	7.00	4.95	5.971
	7.84	5.23	6.536	7.07	4.45	5.759
Avg	*7.70*	*5.70*	*6.701*	*6.95*	*4.85*	*5.900*

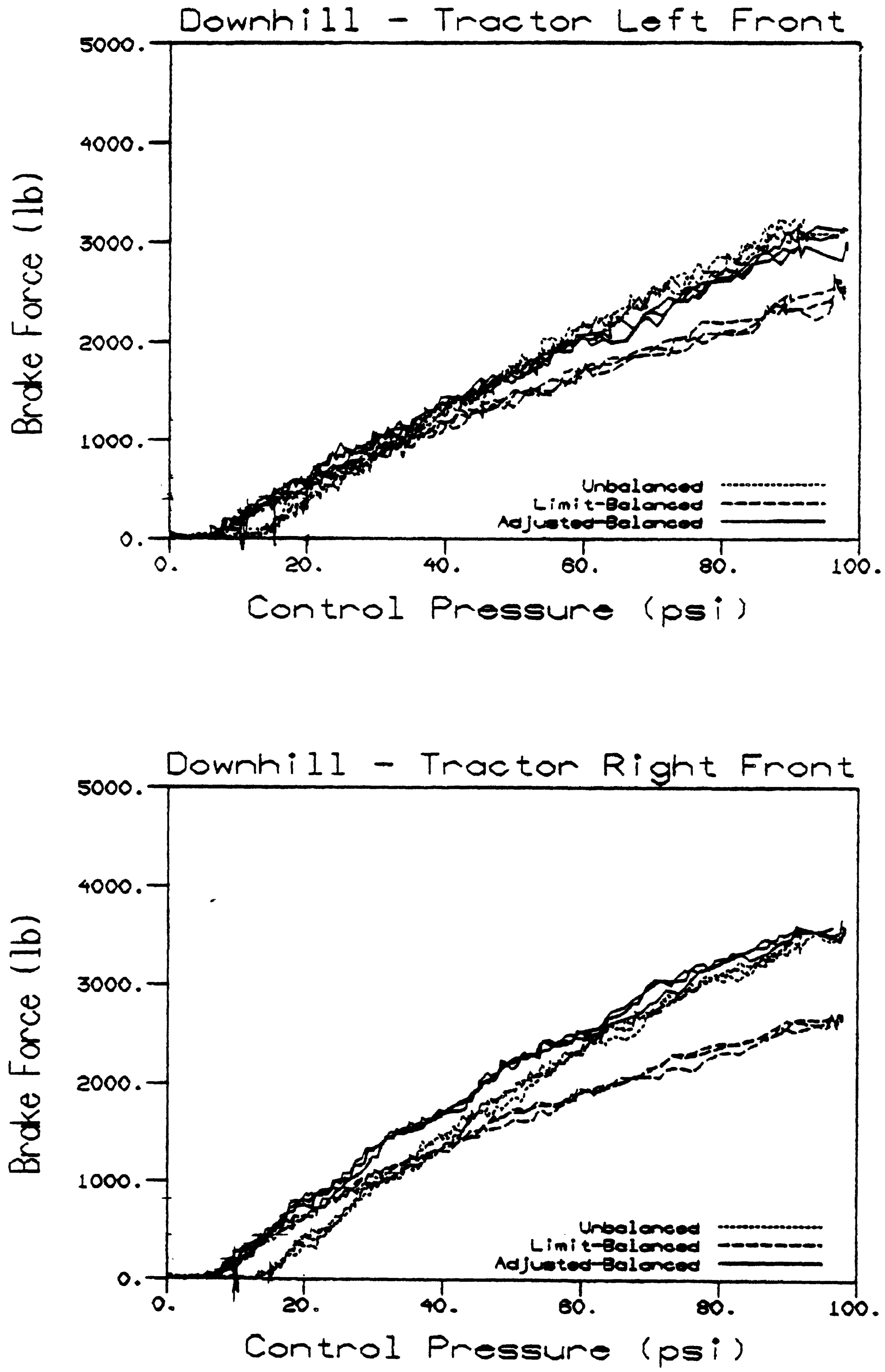


Figure C.2. Roller Dynamometer Results for the 3-S3

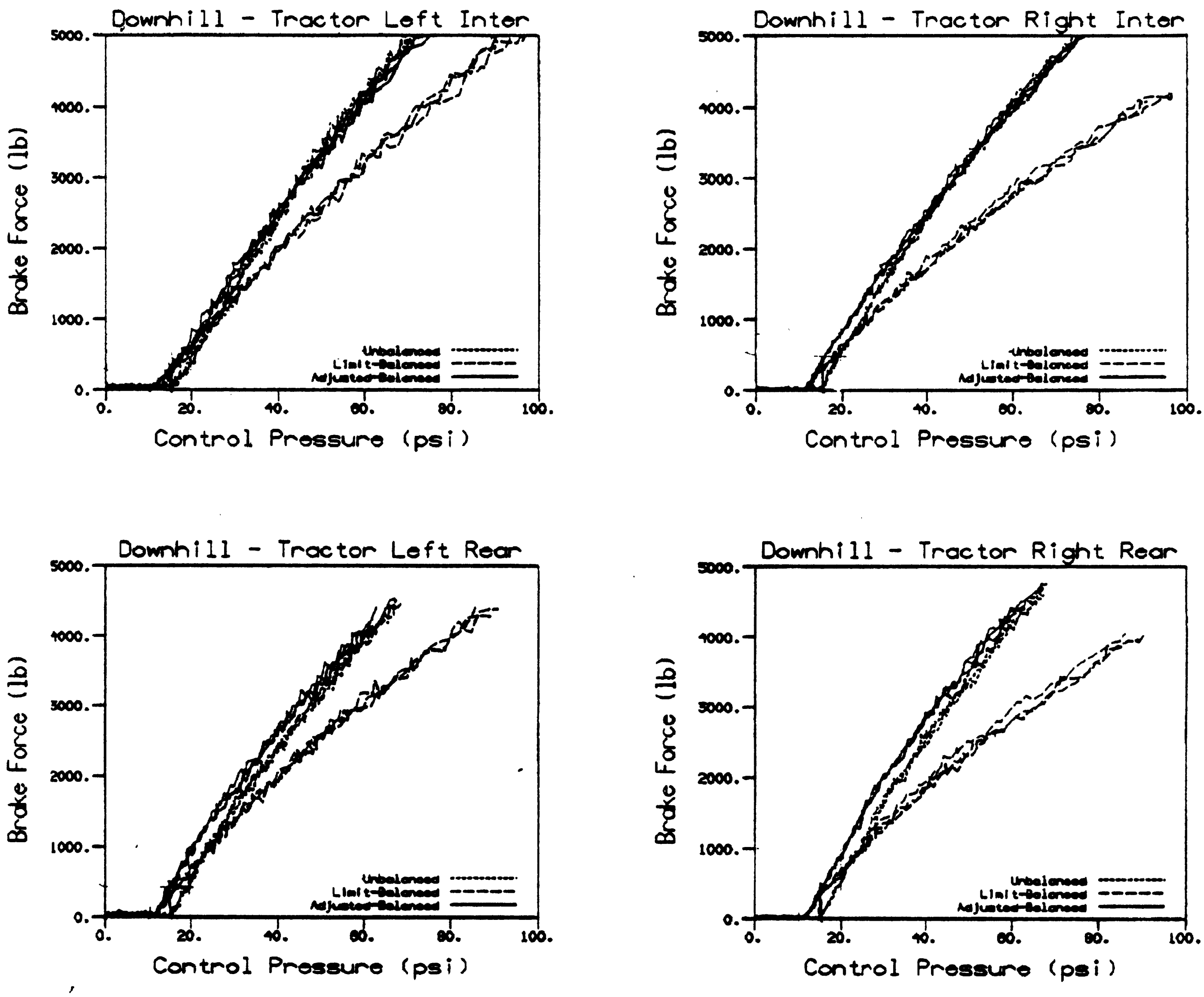


Figure C.2. Roller Dynamometer Results for the 3-S3 (continued)

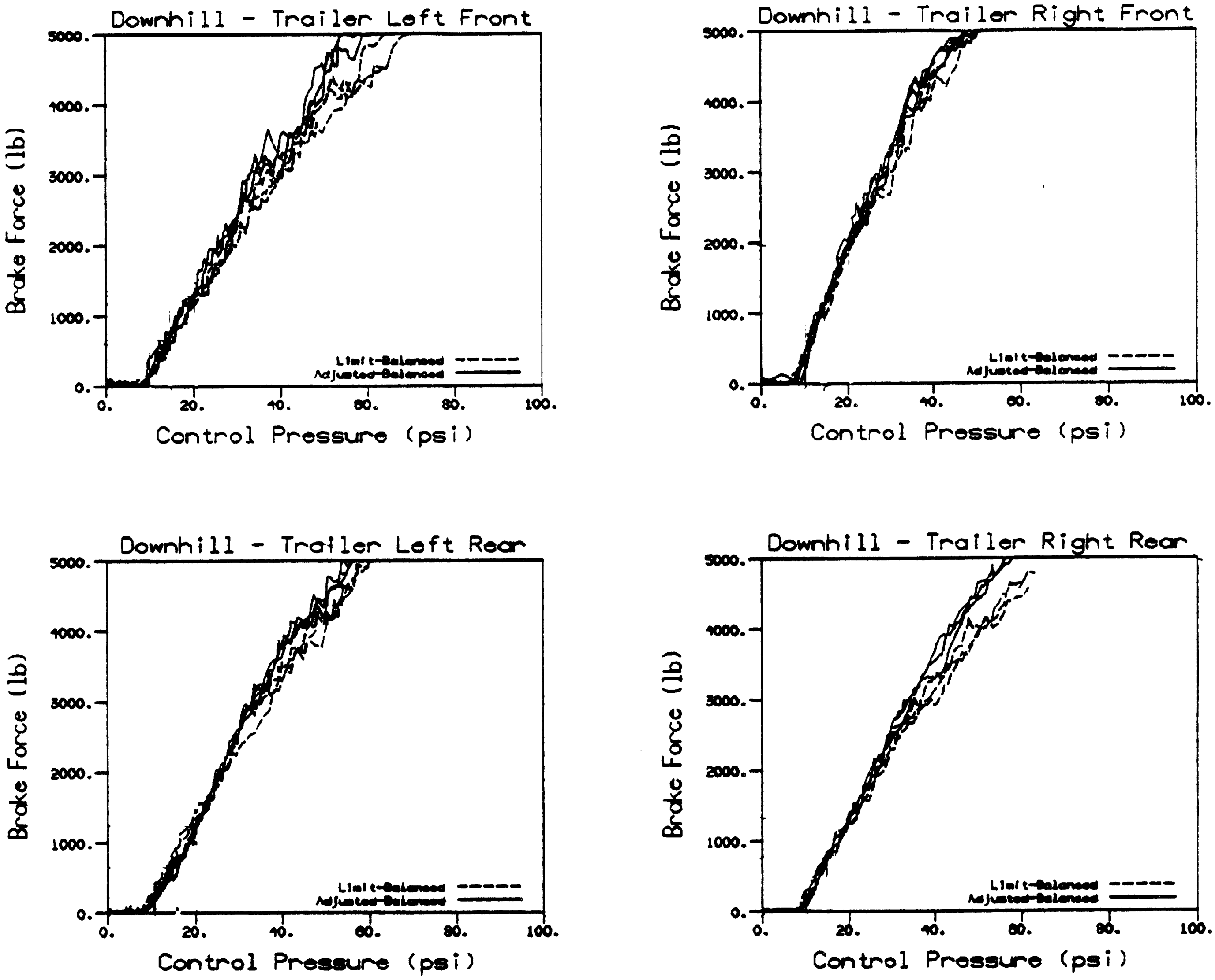
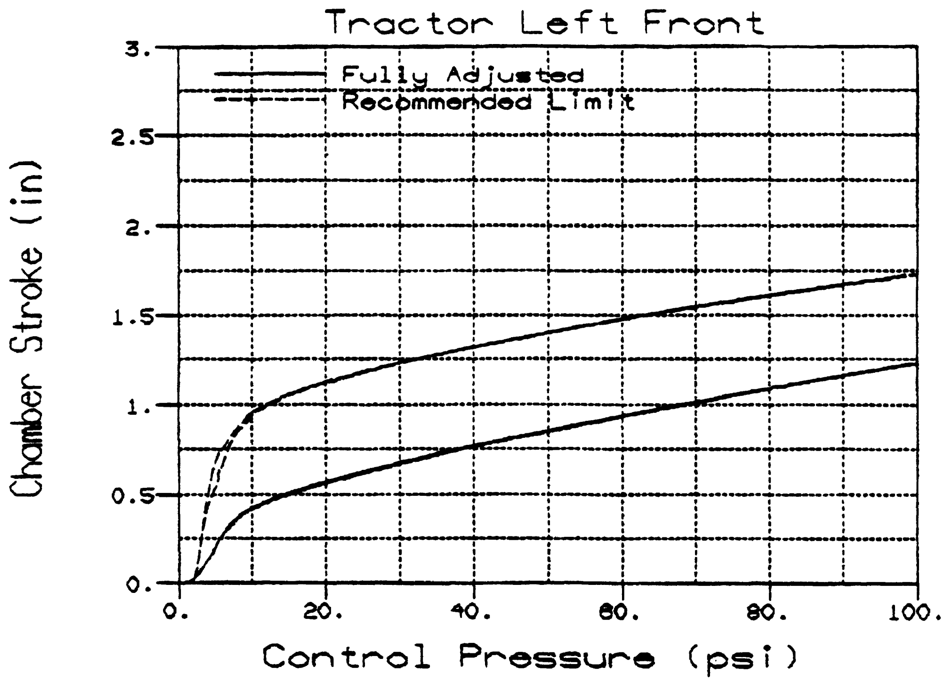


Figure C.2. Roller Dynamometer Results for the 3-S3 (continued)



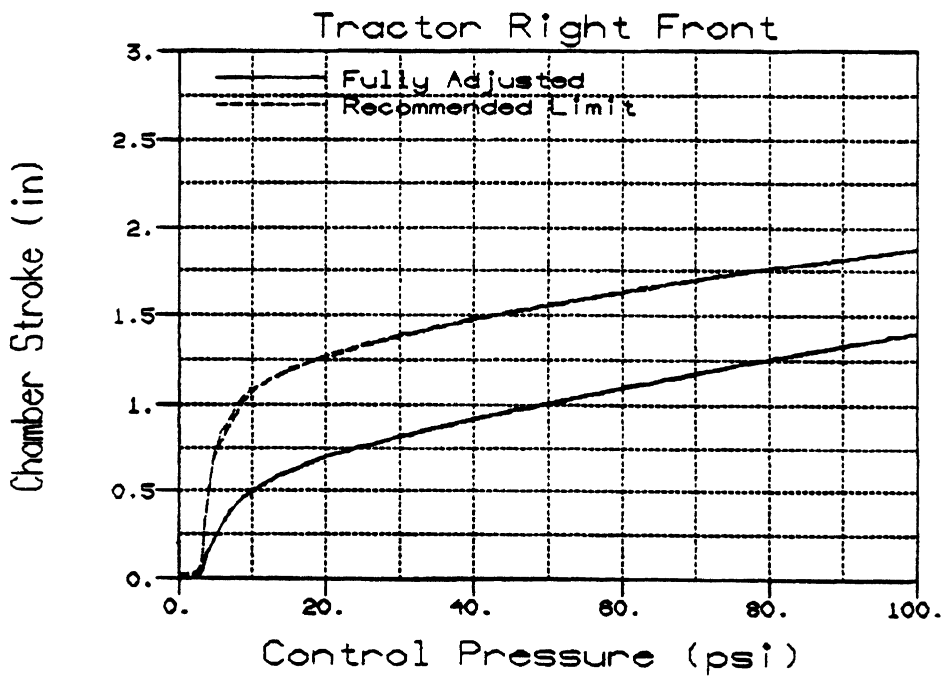


Figure C.2. Roller Dynamometer Results for the 3-S3 (continued)

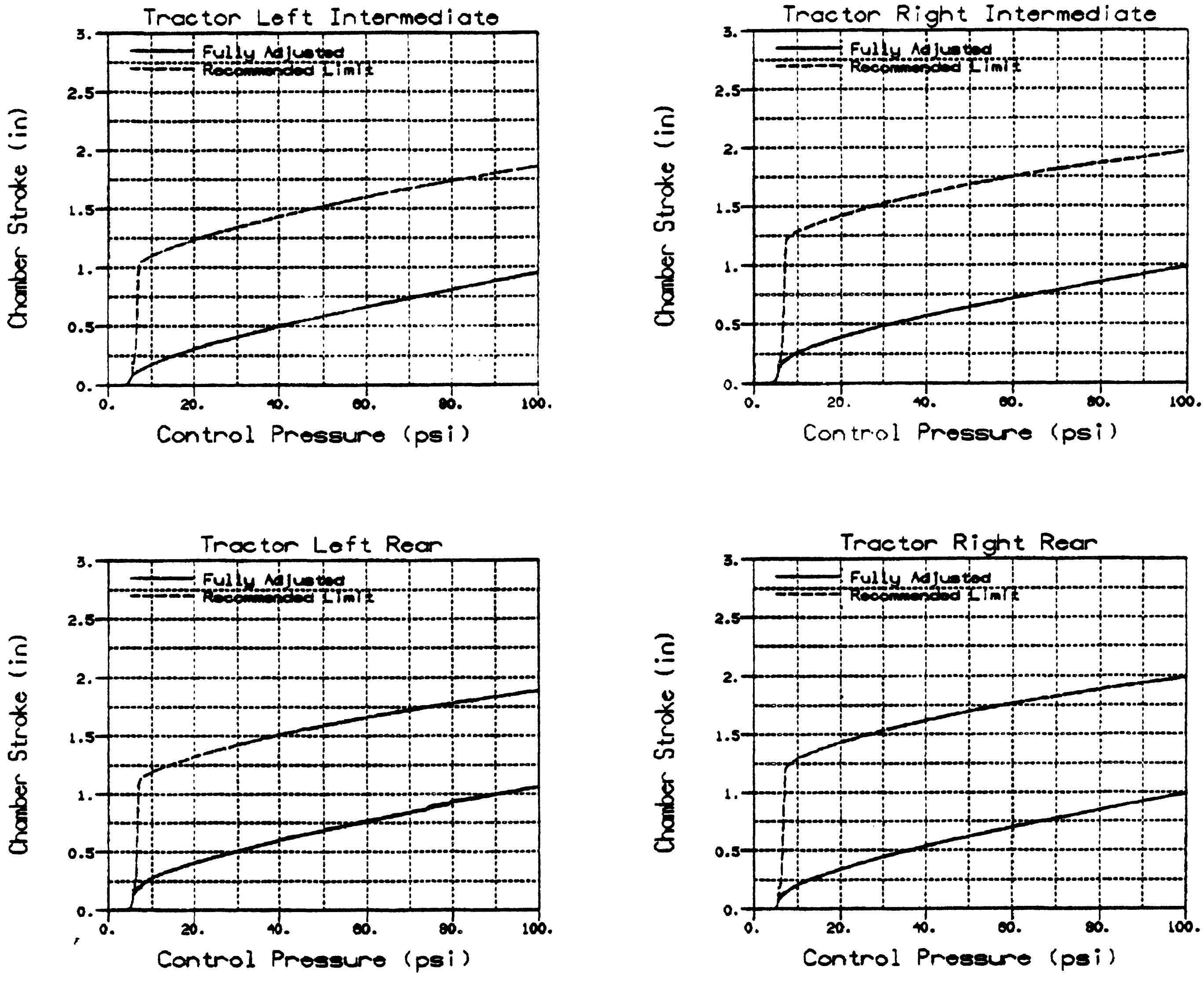


Figure C.2. Roller Dynamometer Results for the 3-S3 (continued)

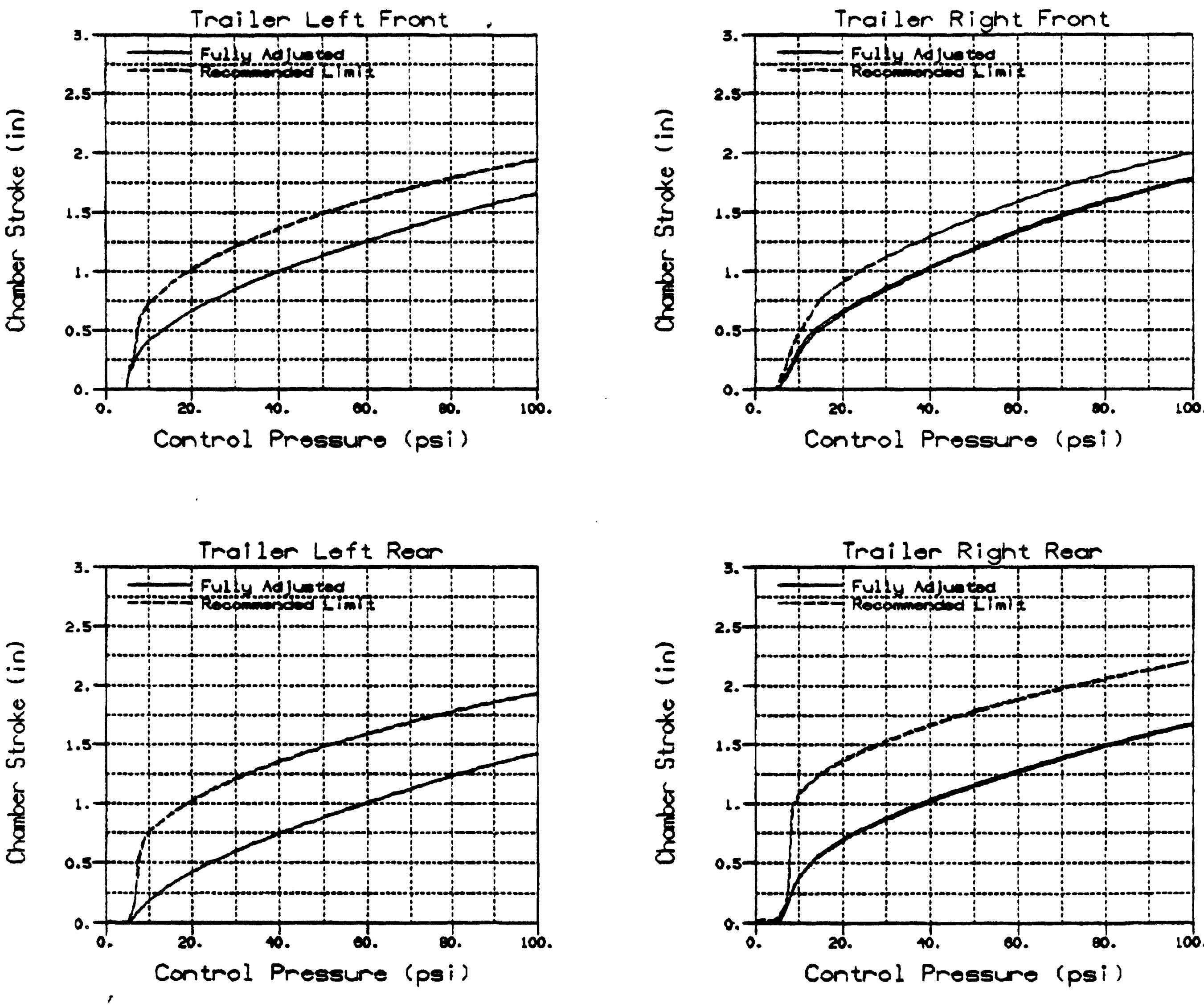


Figure C.2. Roller Dynamometer Results for the 3-S3 (continued)

Table C.2

THRESHOLD PRESSURES - DOWNHILL TEST VEHICLE

	Valves Balanced, Brakes Adjusted						Valves Balanced, Brake at Limit						Valves Unbalanced, Brakes Adjusted					
	Left			Right			Left			Right			Left			Right		
	Ap	Re	Avg	Ap	Re	Avg	Ap	Re	Avg	Ap	Re	Avg	Ap	Re	Avg	Ap	Re	Avg
Tractor Front																		
	9.12	2.12	5.618	7.63	1.98	4.805	10.74	5.09	7.914	7.56	4.24	5.900	16.25	4.45	10.352	14.70	3.96	9.328
	9.61	2.69	6.148	7.84	2.61	5.229	9.47	3.89	6.678	7.98	4.24	6.112	15.40	4.52	9.963	14.27	4.03	9.151
	10.25	3.89	7.066	6.71	2.40	4.558	9.12	4.81	6.960	6.64	4.81	5.724	14.77	4.45	9.610	13.43	3.82	8.621
Avg	*9.66*	*2.90*	*6.277*	*7.39*	*2.33*	*4.864*	*9.78*	*4.60*	*7.184*	*7.39*	*4.43*	*5.912*	*15.47*	*4.47*	*9.975*	*14.13*	*3.94*	*9.033*
Tractor Intermediate																		
	13.71	2.61	8.162	12.58	2.61	7.596	14.84	3.60	9.222	12.65	3.46	8.056	17.74	8.48	13.108	15.90	8.27	12.083
	13.36	3.32	8.338	12.22	2.54	7.384	14.06	3.25	8.656	11.94	2.90	7.420	17.10	7.84	12.472	15.62	7.07	11.341
	14.13	3.46	8.798	12.51	2.83	7.667	13.92	3.67	8.798	12.37	3.18	7.773	17.95	7.21	12.578	15.69	6.78	11.235
Avg	*13.73*	*3.13*	*8.433*	*12.44*	*2.66*	*7.549*	*14.27*	*3.51*	*8.892*	*12.32*	*3.18*	*7.750*	*17.60*	*7.84*	*12.719*	*15 74*	*7.37*	*11.553*
Tractor Rear																		
	12.44	3.18	7.808	12.58	1.84	7.208	13.21	4.24	8.727	12.58	2.97	7.773	17.10	7.63	12.366	15.83	6.22	11.023
	12.22	3.18	7.702	12.01	2.47	7.243	13.57	3.82	8.692	12.51	3.11	7.808	17.17	7.63	12.401	15.76	6.64	11.200
	13.07	3.53	8.303	12.08	2.47	7.278	12.65	3.32	7.985	12.15	3.25	7.702	16.46	7.21	11.836	15.33	6.29	10.811
Avg	*12.58*	*3.30*	*7.938*	*12.22*	*2.26*	*7.243*	*13.14*	*3.79*	*8.468*	*12.41*	*3.11*	*7.761*	*16.91*	*7.49*	*12.201*	*15.64*	*6.38*	*11.011*
Trailer Front																		
	10.25	3.11	6.678	7.77	3.32	5.547	9.89	4.31	7.102	9.26	3.53	6.395						
	9.89	2.83	6.360	8.55	3.39	5.971	9.89	3.04	6.466	8.48	3.18	5.830						
	9.12	3.18	6.148	8.34	3.18	5.759	8.97	2.69	5.830	8.90	2.97	5.936						
Avg	*9.75*	*3.04*	*6.395*	*8.22*	*3.30*	*5.759*	*9.58*	*3.35*	*6.466*	*8.88*	*3.23*	*6.054*						
Trailer Rear																		
	8.55	3.25	5.900	8.41	1.91	5.158	11.59	3.67	7.632	8.69	3.60	6.148						
	10.18	3.32	6.748	8.83	2.05	5.441	9.47	3.60	6.536	8.62	3.60	6.112						
	9.47	3.25	6.360	8.55	2.19	5.370	9.89	3.46	6.678	9.40	3.53	6.466						
Avg	*9.40*	*3.27*	*6.336*	*8.60*	*2.05*	*5.323*	*10.32*	*3.58*	*6.949*	*8.90*	*3.58*	*6.242*						

Table C.3

Timing Data -- TTBRG/SAE/VRTC Commercial Vehicle Brake Distribution Test Program

Tractor: VR- 2 State A in Table 1 Trailer: ____________

	Apply (sec) 0-60 psi				Release (sec) 95-5 psi			
Full Combination:	Run 1	Run 2	Run 3	Average	Run 1	Run 2	Run 3	Average
Front Axle	.325	.323	.328	325	.309	.332	.301	314
INTER Axle	.315	.321	.333	323	.389	.399	.337	375
REAR ~~Trailer~~ Axle	.307	.326	.317	328	.396	.396	.381	391
Tractor Only:								
50 in^3 Reservoir	.311	.326	.321	.319	.655	.634	.638	.642
Trailer Only: (with modified mini tractor at 0.35/0.70 calibration)								
Trailer Axle								
50 in^3 Reservoir								

NOTES: 1) Use shop air to wet tank to give 100 psi in all reservoirs; parking brakes released; start release when lowest chamber is at 95 psi.
2) Full Combination: Use 8 channel recorder at 50 mm/sec.
Tractor Only: Use 8 channel recorder at 50 mm/sec.
Trailer Only: Use modified BAT's transducer and digital readout.

Date Run: 05-02-91 Technician: Lyle + Woody

Timing Data -- TTBRG/SAE/VRTC Commercial Vehicle Brake Distribution Test Program

Tractor: VR-2 State B in Table 1 Trailer: ____________

	Apply (sec) 0-60 psi				Release (sec) 95-5 psi			
Full Combination:	Run 1	Run 2	Run 3	Average	Run 1	Run 2	Run 3	Average
Front Axle	.373	.341	.340	.351	.247	.315	.246	.286
INTER Axle	.336	.347	.334	.339	.443	.391	.404	.413
REAR ~~Trailer~~ Axle	.340	.344	.343	.342	.417	.354	.361	.377
Tractor Only:								
50 in^3 Reservoir	.321	.335	.329	.331	.643	.603	.573	.606
Trailer Only: (with modified mini tractor at 0.35/0.70 calibration)								
Trailer Axle								
50 in^3 Reservoir								

NOTES: 1) Use shop air to wet tank to give 100 psi in all reservoirs; parking brakes released; start release when lowest chamber is at 95 psi.
2) Full Combination: Use 8 channel recorder at 50 mm/sec.
Tractor Only: Use 8 channel recorder at 50 mm/sec.
Trailer Only: Use modified BAT's transducer and digital readout.

Date Run: 05-02-91 Technician: Lyle + Woody

APPENDIX D

HEAT FLOW EQUATIONS

The heating of a brake is analyzed here as a simple process consisting of three parts: (1) the heat flow into the brake due to the rate at which the brake is doing work, (2) the thermal capacity of the brake as determined by its mass (weight) and specific heat, and (3) the heat flow out of the brake (cooling) due primarily to conduction and convection.

The equations presented in this appendix pertain to this simple process. They are good for predicting bulk temperatures of brake drums for slowly changing temperatures such as those that occur during mountain descents. More complicated equations are needed to predict the distribution of brake temperatures across the drum and in the linings as may be of interest in rapid stops. Also, if the brakes become very hot, cooling due to radiation may be important enough to require special terms in the cooling characteristics. Experience, using the equations presented here, has shown that they will provide reasonable predications of brake temperatures if the values of the cooling coefficients are determined experimentally.

The equation describing heat flow is as follows:

$$P = m\ Cp\ (dT/dt) - hv\ (T - Ta) \qquad \text{(D1)}$$

where

P = the energy rate, i.e., the rate of doing work, i.e., the power or heat flow into the brake (ft-lb/sec)

m = weight (lb) (100 lb for example)

Cp = specific heat (approximately 100 ft-lb/lb ^{o}F for cast iron drums)

dT/dt = the time rate of change of the bulk temperature (average temperature of the brake)

hv = cooling rate which is usually treated as a linear function of velocity starting from a rate corresponding to the cooling at zero velocity (ft-lb/^{o}F sec)

T = bulk temperature (^{O}F)

Ta = ambient temperature (^{O}F)

Given values for m, Cp, Ta, and h, differential equation (D1) can be solved for temperature as a function of time if P is available as a function of time. The simplified model, used for making the predictions used in Appendix A, performs this type of calculation for each brake. The power to each brake is determined by the proportioning of braking effort throughout the brake system plus the work rate required to maintain or reduce speed on various sections of the vehicle's route.

In connection with Table 6, equation (D1) has been "integrated" to obtain the following expression which can be solved for the cooling rate (h) at a particular speed (see Table 6 for the resulting equation). For approximately constant velocity,

$$\text{Energy} = m\ Cp\ (Thf - THi) - hv\ [Int(TH) + THA\ (tf - ti)] \tag{D2}$$

where

THf = Final temperature, ^{O}F

THi = Initial temperature, ^{O}F

THa = Ambient temperature, ^{O}F

tf = Final time (braking ends), sec

ti = Initial time (braking starts), sec

Energy = Total work done by the brake, ft lb

Int(TH) = Integral of brake temperature from t_i to t_f, ^{O}F sec

hv = cooling rate, ft lb/^{O}F sec

To experimentally determine h, the energy into the brake (i.e., the work done by the brake) is evaluated (perhaps by integrating the product of brake torque multiplied by wheel speed). The bulk temperature of the brake, as represented by the readings of the thermocouples installed on the outside of the drum, is measured and recorded. Then the integral of the bulk temperature is computed from ti to tf. Once these steps are completed, equation (D2) can be solved for the value of hv at the speed used in the experiment.