U.S. Department
of Transportation
**Federal Railroad
Administration**

TOP-OF-RAIL LUBRICATION ENERGY TEST

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Final Report

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16. Abstract

This report presents the test results of SENTRAEN 2000™, a new top-of-rail lubrication system developed by Tranergy Corporation. The system was evaluated the week of June 2, 1997, at the Federal Railroad Administration's Transportation Technology Center (TTC) near Pueblo, Colorado. The concept of top-of-rail lubrication has demonstrated that it significantly reduces both the energy needed for trains, as well as the lateral wheel/rail loads on curved track. However, it was not possible to determine the exact amount of energy saved as the lubricant application rate left a residue on the rail which eventually led to locomotive wheel slip in the following trains. Electrical energy savings with this system, not including energy generated in dynamic braking, ranged from 23 percent to 30 percent. The average of maximum lateral forces developed in a 7.5-degree curve showed a reduction of 68 percent on the high rail, and 48 percent on the low rail, compared to dry conditions. For the 7.5-degree curve, this lubrication increased the maximum angle of attack from 9 milliradians to 19 milliradians. In dry-rail conditions, lateral forces increase with the angle of attack. However, the increased angle of attack with top-of-rail lubrication did not result in increased lateral forces. It is recommended that evaluations be repeated after modification to the lubrication application rate have been made. This would allow continuous operation without the buildup of residue behind the train.

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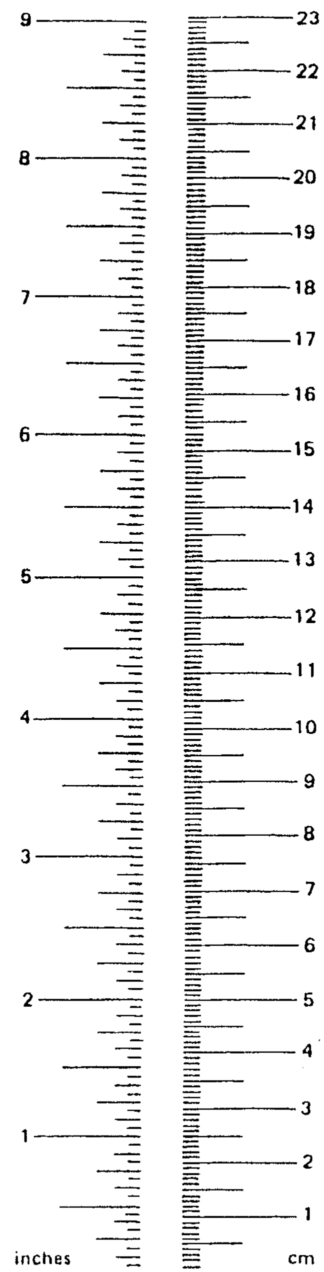
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

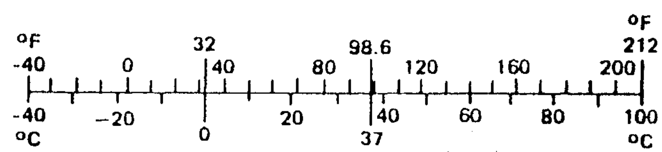
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
		AREA		
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha
		MASS (weight)		
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t
		VOLUME		
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0 76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 cm (exactly)



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi
		AREA		
cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares (10,000 m^2)	2.50	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2 2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius° temperature	9/5 (then add 32	Fahrenheit temperature	°F



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1.0 SUMMARY OF RESULTS

This report summarizes findings and observations made demonstrating the SENTRAEN 2000, a top-of-rail lubrication system produced by Tranergy Corporation. It was evaluated during the week of June 2, 1997, at the Federal Railroad Administration's Transportation Technology Center (TTC) near Pueblo, Colorado. This report also recommends future direction for testing, evaluation, or demonstrations.

The concept of top-of-rail (TOR) lubrication has demonstrated its capability of significantly reducing the amount of energy required to move a three-locomotive, 56-car train; however, during these trials the application rate utilized caused wheel slip to occur after the fourth train passed. This wheel slip might be eliminated by reducing the application rate of the lubricant.

Top-of-rail lubrication also resulted in significant reduction of lateral loads applied to the rail. Average of maximum lateral forces developed on a 7.5-degree curve reduced from 16.5 kips to 5.2 kips on the inside (low rail), and from 13.3 to 6.9 kips on the outside (high) rail. Certain car trucks termed "bad actors," however, exhibited a significant increase in maximum angle of attack when lubrication was applied to the top of both rails. This increased angle of attack did not, however, result in increased lateral loads. For a 7.5-degree curve, the maximum angle of attack (AOA) increased from approximately 9 milliradians to 19 milliradians. The average angle of attack increased from 4 milliradians to 5 milliradians.

The objective of this demonstration was to document energy and lateral force (truck curving) reductions from lubricating the top of rail behind the locomotive(s). The TOR lubricant evaluated is metered and applied with the intention that it will be consumed within the train and will not leave a residual trace on top of the rail after the last car that might result in reduced friction to leading locomotives of following trains.

Traditional gage-face lubrication is applied by various combinations of wayside, hi-rail and locomotive flange lubricators, with the objective of lubricating the flanges of passing wheels. Most traditional lubrication systems apply extra lubricant which is not consumed within the train. The remaining lubricant on the gage face results in a "reservoir" of lubricant, which can become excessive, or migrate to the top of rail. Migration and inconsistent application of lubricant in an uncontrolled fashion by conventional lubricators can lead to higher lateral loads and reduced energy savings. A conventional locomotive flange-lubricator system was also tested to allow comparisons to be made.

The SENTRAEN 2000 system adjusts lubricant output rate based on curvature. This was verified by monitoring output during the test. While the initial analysis of data and field observations collected during the demonstration of the top-of-rail system at the TTC indicated a reduction in energy and lateral forces, a residual amount of lubricant remained after the last car of each train pass. It appears that the application rate was too high, or the lubricant performance too durable, for all of the product to be consumed within the length of the train used in this test. The result was an undesirable buildup of lubricant on the top of rail which resulted in locomotive wheel slip in both traction and dynamic braking on the fourth lap. During these trials any lubricant application rate which produced a measurable amount of energy savings also left a residue on the rail which eventually led to wheel slip in following trains.

The conventional locomotive flange lubricator evaluated during this same test period did not exhibit wheel slip. However, examination of locomotive traction data indicates that the trailing locomotives in the consist were showing conditions similar to that when wheel slip occurs.

Electrical energy savings with the top-of-rail system, not including energy generated in dynamic braking, ranged from 23 to 30 percent. The savings varied depending on if the comparison was made from a dry or contaminated rail (contaminated rail is a rail with a small amount of pre-existing lubrication). This savings is route-specific to the test loop and train that was evaluated for this test. Other routes, with fewer grades and/or curves, may result in different percentages of energy savings. With the application rates evaluated, the top-of-rail (only) lubrication resulted in greater energy savings than the conventional gage-face (only) system. Combining conventional gage-face lubrication with top-of-rail lubrication did not add additional energy savings over and above that observed from using only the top-of-rail system.

Attempts were made to reduce the lubricant application rate by adjusting control-system parameters and operating repeated passes with the system alternately turned on, then off, to simulate a longer train. In all cases, the top-of-rail product rapidly (within three to five passes) accumulated on top of the rail to a level that led to locomotive wheel slip. It is recommended that evaluations be repeated after modifications to the lubrication application rate have been made to allow continuous operation without buildup of a residue behind the train.

2.0 TEST PROPOSAL/PLAN

The test plan presented to Federal Railroad Administration (FRA) and Department of Energy (DOE) was based on initial input and discussions with DOE representatives and addressed energy, lateral load, and other train-performance improvements claimed by Tranergy Corporation for the company's SENTRAEN 2000 top-of-rail lubrication system. These issues were supplemented by specific areas addressed by railroad personnel participating in the test program. These included train braking, truck and car hunting, and energy reductions on long tangents. The test plan was laid out to address these issues, and in some cases, results of one step were needed to build onto future steps.

2.1 ENERGY AND TRUCK-PERFORMANCE ISSUES

Energy: The primary purpose of the test from the DOE perspective was to document reductions in energy when lubricating the top of rail. This was to be accomplished in two stages. The first part of the test was operated over the TTC's 3.3-mile wheel rail mechanisms (WRM) loop, which contains a range of curvatures from 3 degrees to 12 degrees. With little tangent track between curves, this could be considered a rigorous environment with severe curving and flanging friction conditions when compared to tangent (straight) trackage. Past studies of rail-gage-face lubrication systems on this and other similar test loops at the TTC have shown energy savings from a dry to lubricated condition range from 15 percent to more than 32 percent, depending on train condition, lubricant performance, and applicator reliability.

The test plan called for initial operations to be conducted over the WRM loop with two train lengths (25 and 75 cars), however due to a lack of a sufficient number of donated cars, long train operations were conducted with 52 to 62 cars. The variation in train length would also be supplemented with two variations in application rate of the lubrication. This was intended to allow AAR to investigate normal and over-lubrication rates, and allow the vendor to evaluate the effect of different amounts of lubrication. The plan was to then relocate the train onto the TTC's Railroad Test Track (RTT), which is a 13.5-mile loop made up of very mild curves and long tangents. Energy testing, along with stop-distance braking and hunting tests, would be conducted on this loop to assess the energy savings of top-of-rail lubrication on a track where little or no flanging would occur.

Energy testing can incorporate a large number of variables and parameters. However, by keeping the same train consist, train speed, crew, locomotives, and track and weather conditions, basic comparisons can be made between "blocks" of operations. By operating a train around the loop at a consistent speed (that is, keeping the train at a constant speed at specific locations regardless of train resistance), changes in resistance due to lubrication can be associated with changes in energy needed to maintain identical train speeds.

For each lubrication condition, a train operation to establish a new "dry baseline" was conducted. Energy and other data (outlined below) were collected for the dry baseline and subsequent lubricated laps. Comparisons are best made between consecutive periods. At times, however, a residual level of lubrication remained on the rail, and the dry baseline was not as "dry" as others. For this reason, a range of potential savings is shown relative to two baseline conditions — dry and contaminated.

Lateral Loads and Truck Curving: Truck curving performance can be significantly affected by rail and wheel friction. An improper balance between high- and low-rail friction can lead to truck warping. Such a condition can result in increased lateral loads. Truck warp (from reduced steering moments resulting in high angles of attack) can also lead to increased vehicle component wear. Separate wayside measurements were made on curves of the WRM loop to evaluate loading and curving performance under varying lubrication conditions. Representatives of each parameter are included in this report to assist the reader in understanding the conclusions and recommendations. A recommended lubrication practice is one that reduces energy consumption while at the same time results in the least increase in lateral loads and truck warp.

2.2 OTHER ISSUES

Other issues addressed included mixing conventional lubrication with the top-of-rail system, simulating partial top-of-rail systems failure, over-lubrication, train braking, and car hunting, as follows.

Conventional and top-of-rail lubrication mix: If the "behind-the-locomotive, top-of-rail lubrication concept" is to be implemented, it would likely need to be carried out system-wide. During the transition period, however, some traditional wayside, hi-rail and/or locomotive flange lubrication systems may still be in operation. To evaluate the effect of mixing top-of-rail lubrication onto the pattern that may exist on the rail from flange lubricators, a conventional locomotive flange lubricator system was utilized to create a typical gage-face lubricant condition. The procedure followed was to lubricate the rail from a dry condition, establish a "conventional lubricated gage face," then add the top-of-rail lubricant and determine changes in forces, additional energy savings, and monitor any side effects in train handling.

Partial system failure: The effect on forces and energy of a partially disabled top-of-rail application system was to be monitored. Although a remote possibility, an example of how such a situation could occur would be if ballast particles were kicked-up and misaligned an applicator nozzle. This could cause one rail to be lubricated and the other to remain dry, which might result in higher lateral loads due to an imbalance of truck steering forces. Wayside data collected during this simulated damage or malfunction was intended to determine changes in lateral rail forces.

Over-lubrication: The SENTRAEN 2000 top-of-rail lubrication control system requires trailing tonnage information in order to adjust and meter the correct amount of lubricant. The lubricant application rate is adjusted for curvature, temperature, and speed to apply the correct amount of lubrication. In order to evaluate the effects of a train crew error in establishing tonnage adjustments resulting in over-lubrication, a short 25-car consist would be operated. The plan was to determine energy savings of a short consist along with measuring the amount of lubricant remaining after the train passage. This was intended to compare end-of-train carry-over from the longer train, which was designed to disappear and not leave a lubricating film after the last car.

Train braking: A concern raised by representatives from member railroads was that train braking could be compromised by applying lubricant to the top of rail. The plan was to evaluate braking issues by two methods; namely, measuring stop distance and noting any wheel slip or lockup during air brake applications.

Truck hunting: Truck hunting can be reduced by top-of-rail lubrication. Truck hunting data was to be taken at the front, middle, and end of a long train operated at hunting speeds (50 mph) on the RTT. This would allow comparisons of truck hunting to be made under various top-of-rail lubrication levels.

3.0 LOG OF TESTING AND CHANGES MADE DURING THE TEST

The test period ran from June 2 to June 6, 1997. This report shows only details of testing accomplished on June 5. This was the day when the most significant data was gathered. This is summarized in Table 1. A brief summary of other test days is shown as information. Generally, all operations started at or near midnight and proceeded for up to 12 hours. This allowed operations to be conducted during the coolest part of the day for safety purposes and when wind-speed effects were negligible.

The test control log shows and numbers each and every train pass, while energy data is valid only for laps where a consistent speed was maintained. During testing, every time the train was started or stopped those particular laps would not have representative speeds, train handling, or energy, and thus are eliminated from all energy plots. Wayside data was taken almost continuously, and train passes were often at constant speeds — thus this database generally contains more laps with valid data. Since the data plots show consecutive laps, and not actual lap numbers, the test control log does not correspond directly to the wayside energy data for lateral force and AOA.

All lubrication application rates were adjusted by the vendor, and were considered proprietary. The only indication provided to the test personnel was a "divide by code xx" number. The larger the "code xx," the less lubricant was applied. These are shown in the Table 1 and in the summary of Day 4 testing.

Summary of Day 1-5 Activities

Day 1 — June 2: The dry rail baseline was established with a 25- and 62-car consist. Prior to testing, the AAR had machined the wheels on 10 cars — five cars with a new wheel taper, and five cars to a hollow-worn profile — in order to collect data on the effects of lubrication on such wheel profiles. After discussions with the sponsors at the pretest meeting, it was decided that the five cars fitted with hollow wheels were not representative of typical revenue-service worn-wheel conditions and in-truck positions, and might adversely affect performance of the lubricant and train. The group consen-

Table 1. Details of Testing for June 5— Date on which Most Significant Data was Gathered

TRAIN PASS	CONDITION	COMMENTS
1	Dry/Baseline	Train speed slow — no data
2-6	Dry/Baseline	Train at speed — begin data laps
7-14	Flange Lubricator	Turn on at summit lubricator set at nominal rate
15	Flange & TOR Lubricators	TOR system set at Code 78
16	Flange & TOR Lubricators	Dynamic brake wheel slips
17	Flange & TOR Lubricators	Power and dynamic brake wheel slips
18-19	Flange & TOR Lubricators	TOR system set at Code 130 Power and dynamic brake wheel slips
20	Flange & TOR Lubricators	No wheel slip
21	Flange & TOR Lubricators	Power and dynamic brake wheel slips
22-26	Flange Lubricator	Turn off TOR system due to wheel slips
27-32	Dry Down	Turn off all lubricators
33	Dry Down	Stop to fuel locomotives — no data
34	Dry Down	Train speed slow — no data
35-38	Dry Down	Train at speed — data laps Residual lube still present — use locomotive sanding and power braking to help dry track
39-40	TOR Lubricator	TOR system set at Code 130
41	TOR Lubricator	Power and dynamic brake wheel slips
42	TOR Lubricator	TOR system set at Code 250 Power and dynamic brake wheel slips
43	TOR Lubricator	Dynamic brake wheel slips
44	TOR Lubricator	Power and dynamic brake wheel slips
45-49	Dry Down	Turn off TOR system due to wheel slips Dry down using locomotive sand and power braking
50-52	TOR Lubricator	TOR system set at Code 250
53		Power and dynamic brake wheel slips
54	No lube	Stop train at bottom of 2 percent grade and misalign TOR application nozzle on the inside rail — No data
55	TOR Lubricator misaligned	Power wheel slips
56	TOR Lubricator misaligned	No wheel slips
57	TOR Lubricator misaligned	Power and dynamic brake wheel slips
58-71	Dry Down	Dry down using locomotive sanding and power braking No data

sus was to remove the five-car block of hollow-profile wheels installed by the AAR, and repeat the baseline runs. Also at this time, additional detailed inspection of the donated tank cars indicated some contained wheels with marginal flange conditions and these also were removed.

Day 2 — June 3: Testing started by repeating the dry baseline runs with 25- and 56-car consists. This required about four hours of operation. The 25-car consist did not contain any recently machined wheels. After the dry baselines were re-established, the top-of-rail lubrication system was turned on to evaluate energy savings using a 56-car consist. The lubrication system experienced operating difficulty, and did not apply lubricant. For the remainder of the shift, various trouble-shooting techniques were tried by the vendor, and the system was deemed operational at the end of the shift. The rail condition was left somewhat lubricated due to time constraints of the operating crew.

Day 3 — June 4: Train operation began with some dry-down laps to remove contamination from the rail. Following this dry-down, the test resumed with top-of-rail (only) lubricated operations, and continued for the entire day. During initial and all subsequent operations of Day 3, after three to five laps with the top-of-rail lubrication "on," wheel slip occurred. Inspection of the rail after each train pass indicated that a residual amount of lubricant remained, which eventually built up to the point at which locomotive wheel slip occurred. This occurred during dynamic braking at speeds of about 30 mph, and under full tractive power at 15 to 20 mph. After wheel slip occurred, the lubricator was turned off for several laps to dry the rail down, the train stopped, lubricator rates adjusted to a lesser amount by the vendor, and the train restarted.

A number of attempts were made by the vendor to reduce the amount of lubricant. This included reducing the application rate, changing the control board to allow less application, and operating a series of laps successively with one lap "on," and one lap "off" to simulate a double-length train. In every case, after three to five passes, the train crew reported significant locomotive wheel slip. During all of these operations wayside lateral data and on-board energy data were collected. However, steady-state energy levels could not be maintained due to the need to stop lubricating and avoid wheel slip. The occurrences of wheel slip significantly affected the accuracy of the energy data. Figure 1 shows the energy values measured on the locomotives with respect to distance for two consecutive lubricated laps on Day 3. The data shows significant jumps in the energy in the distance range of 15,000 feet from the starting point. Wheel slip phenomena make the energy values surge, and thus nullify the energy data for such laps. For this reason, no steady-state energy data could be generated during any day of this test under top-of-rail lubrication (only) conditions.

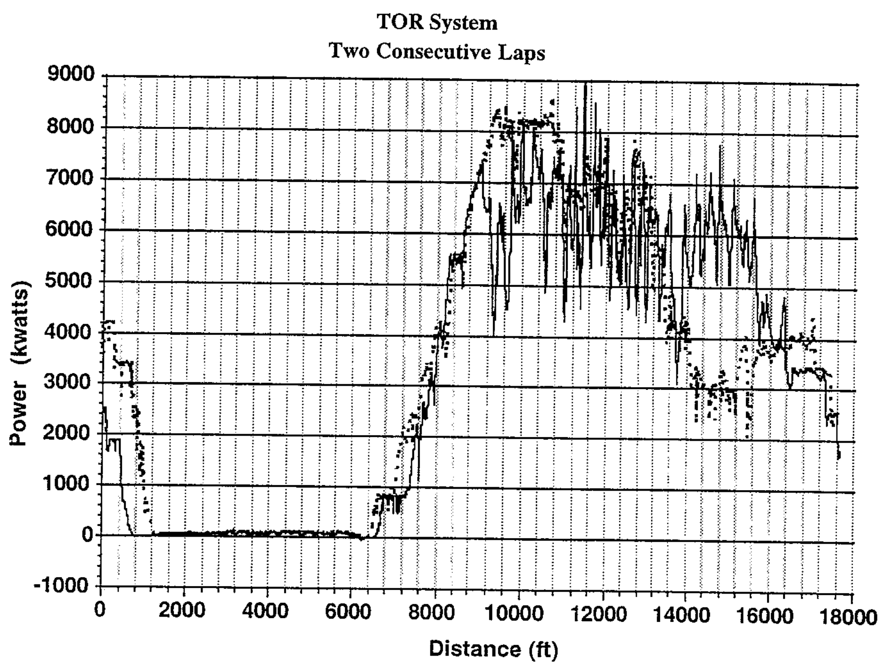

Figure 1. Energy Plot by Train Pass for Day 4

A concern was raised that the short loop operation did not leave sufficient dwell time from the passage of the last car to the passage of the next train. On the WRM test this was about six to seven minutes per train pass. It was suggested that in revenue service the longer dwell time between trains (usually 20 minutes or longer) would allow the lubricity of the lubricant to dissipate, and the problem of lubricant buildup would not occur. To address this issue, the track was left in a lubricated state at the end of testing. A tribometer crew was kept on an extended shift to measure top-of-rail friction for three additional hours, or until the lubricant dissipated. Initial top-of-rail friction was measured at 0.35, and after three hours with no train, the friction remained at 0.38 and the crew was dismissed. It was determined that within the three-hour window the lubricant dissipated only with train action, and not time.

At the end of the shift the vendor indicated that the system could not be adjusted any lower with the physical configuration of the system at that time, and the decision was made to continue with test plan requirements to evaluate combined gage-face and top-of-rail application systems and simulated damaged applicators by lubricating only one rail.

An on-site discussion was held with railroad representatives, and it was agreed that an acceptable application rate that did not build up or leave a residual film had not yet been demonstrated. Thus a "representative" top-of-rail lubricant pattern could not be reliably operated on other TTC test tracks. As all application rates evaluated resulted in wheel slip, it was agreed that braking tests would not be prudent as wheel slip would likely happen and damage to wheels was to be avoided. Additional operation with a short (25-car) train was also canceled, as the primary reason for this was to evaluate over-lubrication conditions. The lowest application rate tended to over-lubricate a 56-car train, thus it was deemed redundant to over-lubricate an even shorter train. In addition, since a "within the train, front to rear" differential in lubrication effectiveness was not observed, based on wayside data, the hunting tests were also canceled. The rationale for the hunting tests was to determine if more lubrication at the front of the train had a different effect on hunting than at the end of train, where lubricant effectiveness was intended to be much less.

Day 4 — June 5: For this report, figures 2-27 show energy and wayside data summarized for all runs during Day 4, as this day includes the most important variations and operating conditions. Figure 2 shows energy data for all test conditions (dry, flange, and top-of-rail lubrication) during Day 4. Figure 3 summarizes energy savings observed for each lubrication condition. This was calculated using the average steady-state energy for each condition, compared to the dry baseline.

Prior to starting the shift, a train inspection indicated four additional cars had received excessive wheel-flange wear, and were removed from the consist. This resulted in a 52-car train. For this reason, along with the need to remove residual lubrication remaining from the previous day's top-of-rail operations, a new dry baseline was established for energy comparisons. It is important to note that energy data collected during Day 4 can only be compared to data taken with the 52-car train, and not with any previous runs.

After the track was again dried down, a new dry-rail baseline was established. Lead, middle, and trail locomotive power for a typical dry lap is shown in Figure 4. Conventional flange lubrication was then applied from two locomotive lubricators. After five laps of application, the energy data indicated a steady-state level, and four additional laps were operated to establish a gage-face friction condition and energy level. During this period, although no wheel slip was recorded or observed, post-test evaluation of individual locomotive power data indicates that the middle and the trailing units were approaching wheel-slip conditions. This can be seen in Figure 5, where the middle and trail locomotives' volt/amp history shows considerable surging. A similar pattern can be seen in Figure 6 for data collected during top-of-rail testing. In this case all locomotives showed surging. It is likely that if additional laps had been operated with the flange system set at the application rate utilized, locomotive wheel slip would have occurred.

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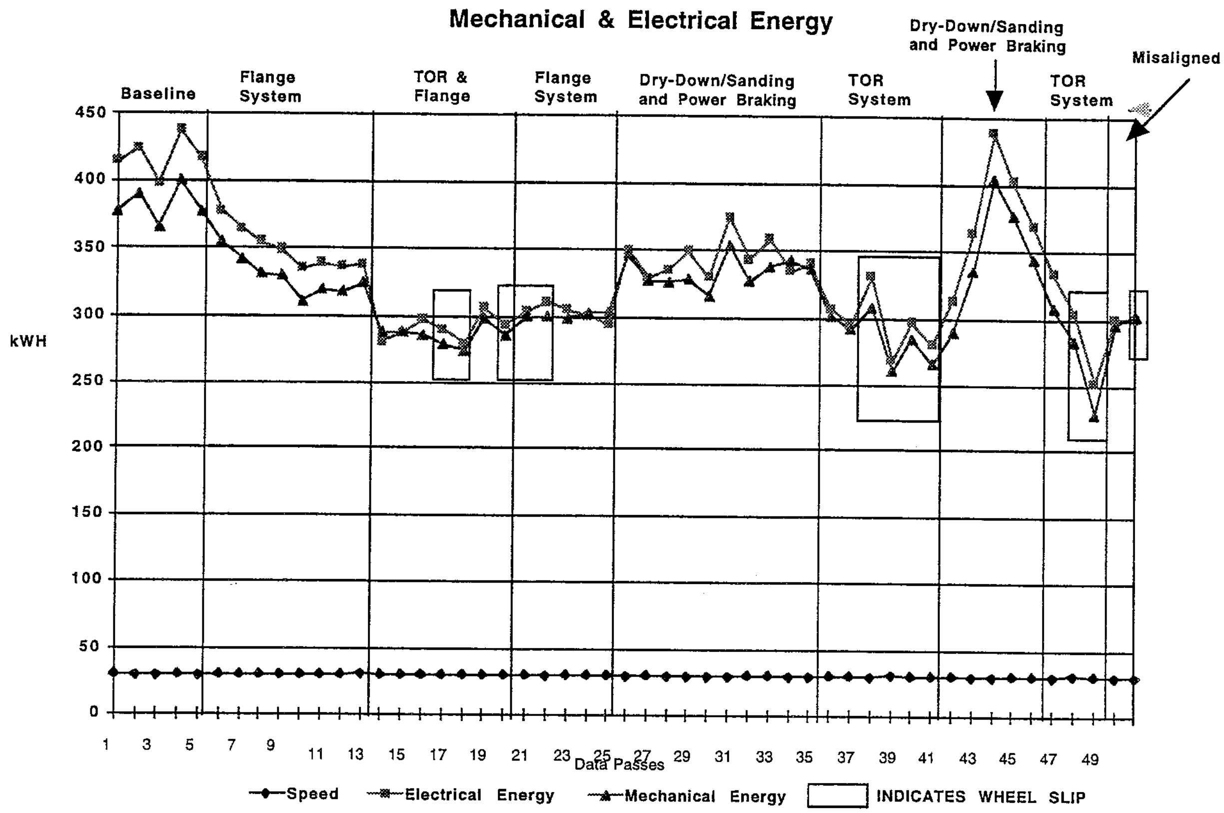


Figure 2. Mechanical and Electrical Energy Summaries for Each Lubrication Condition (Day 4)

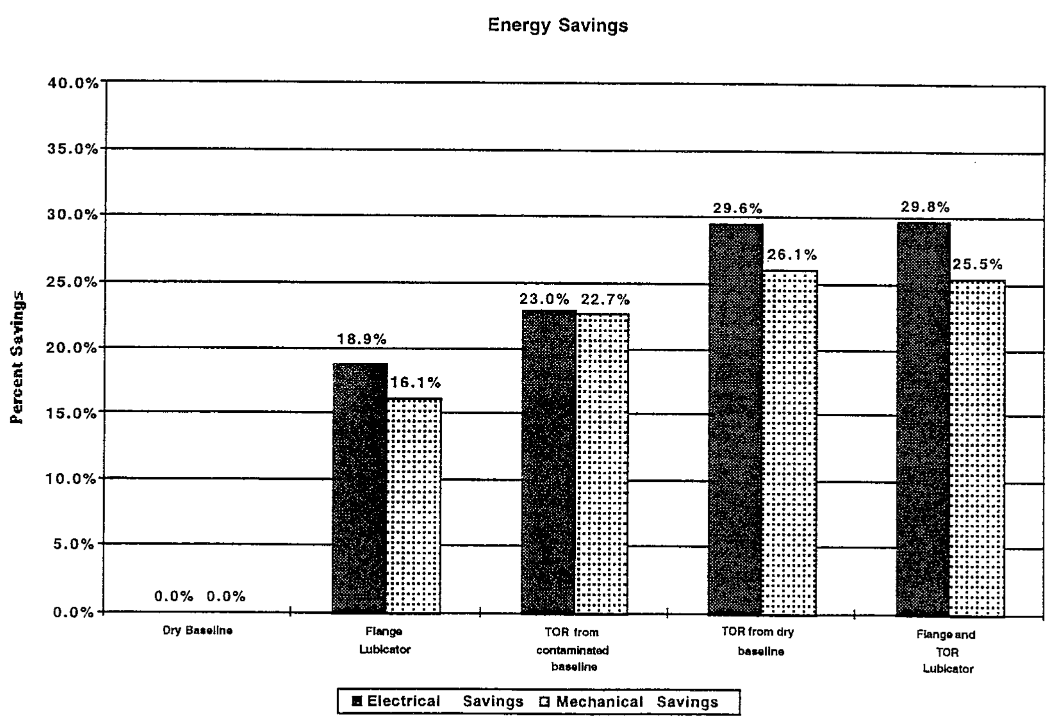


Figure 3. Energy Savings Compared to Dry Rail and Contaminated Rail

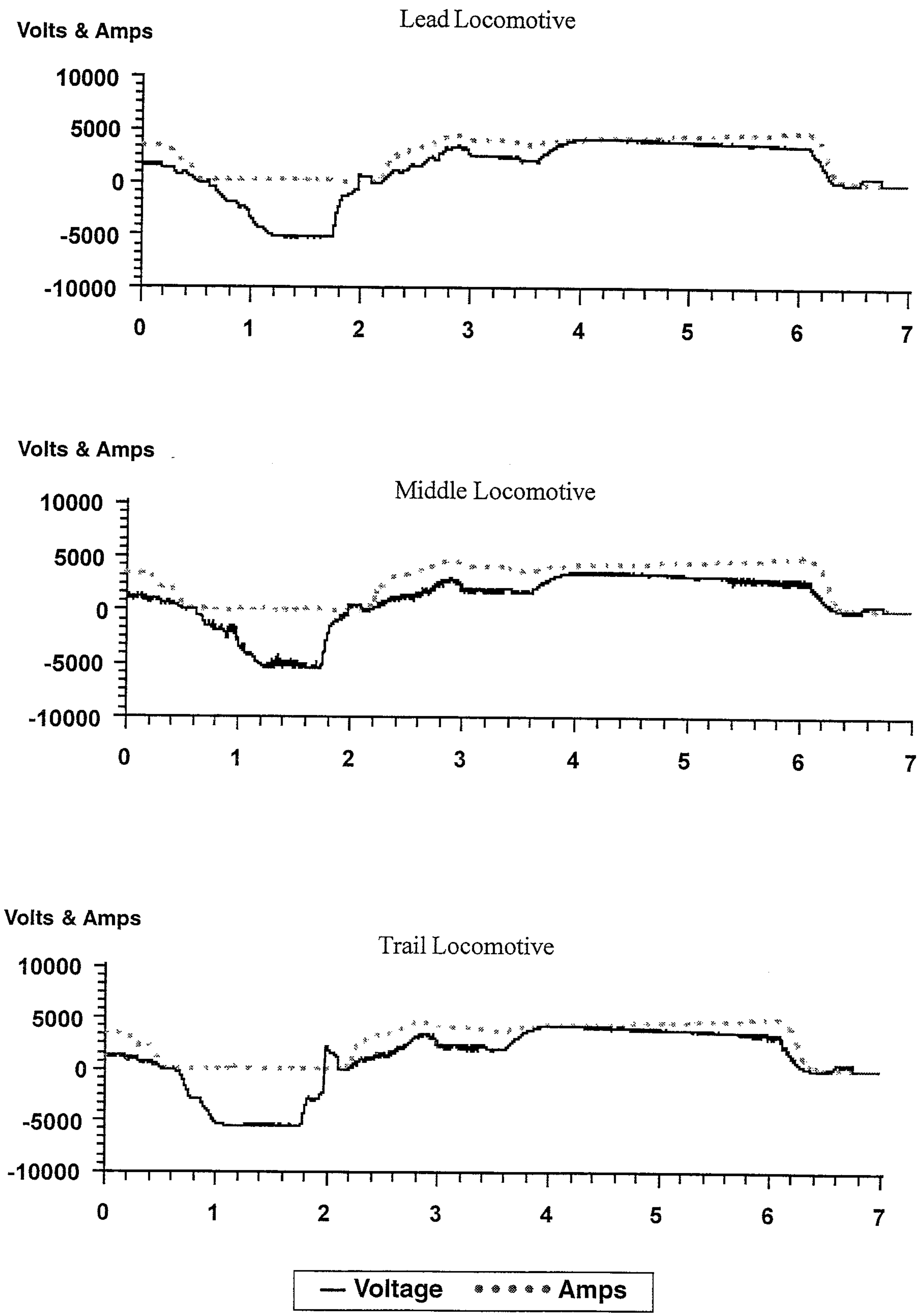


Figure 4. Locomotive Consist Electrical Output — Dry

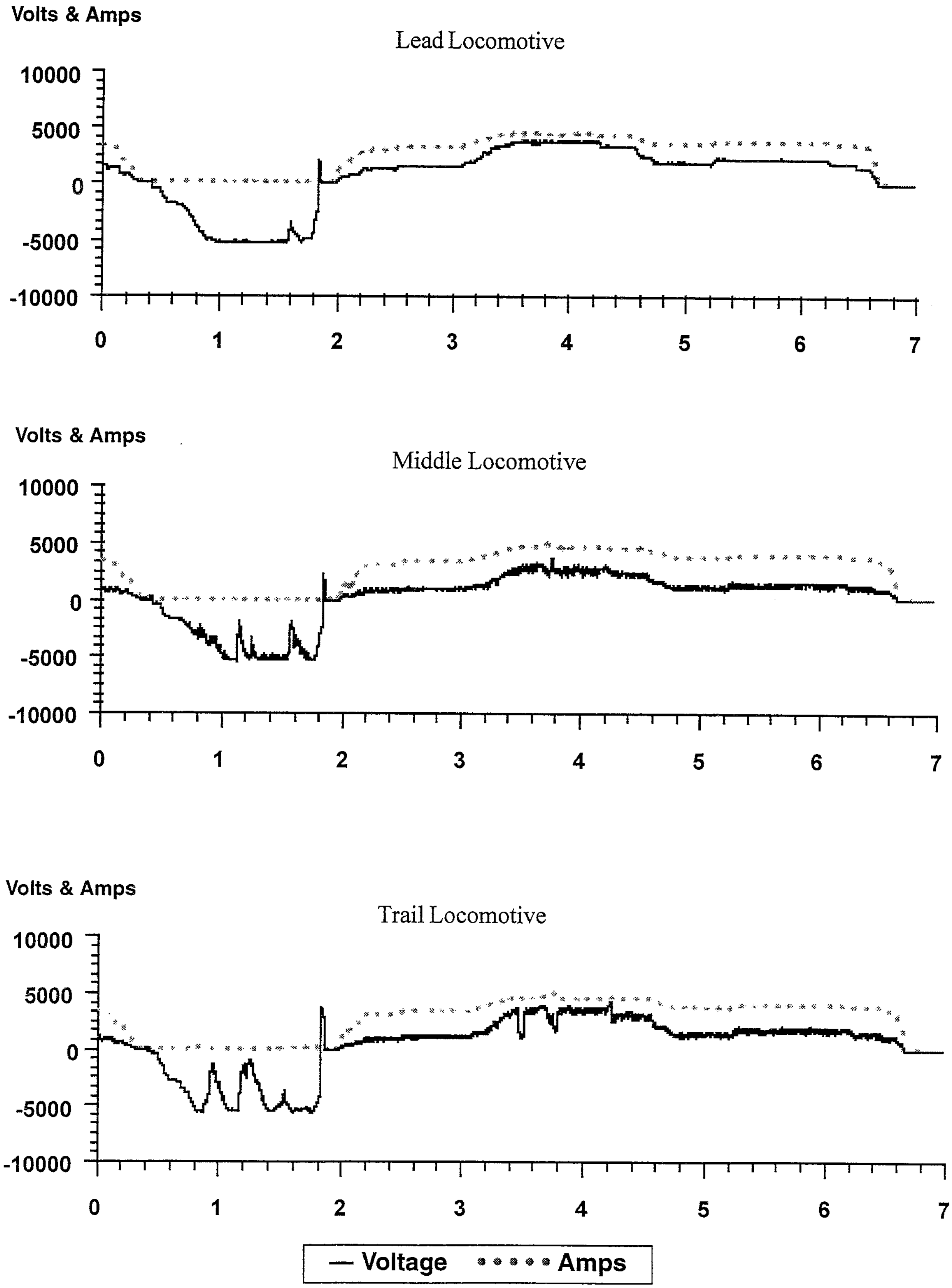


Figure 5. Locomotive Consist Electrical Output — Flange Only

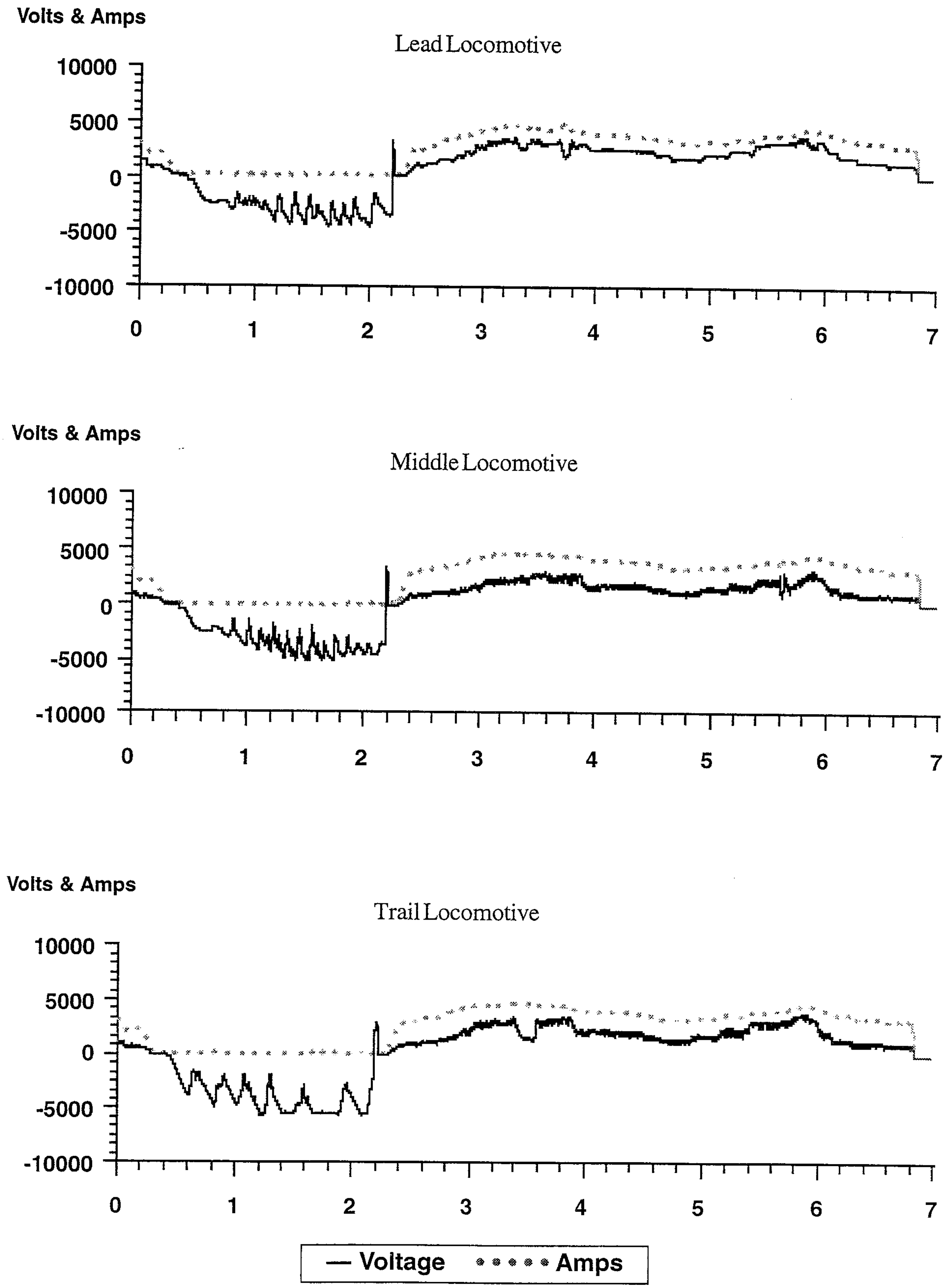
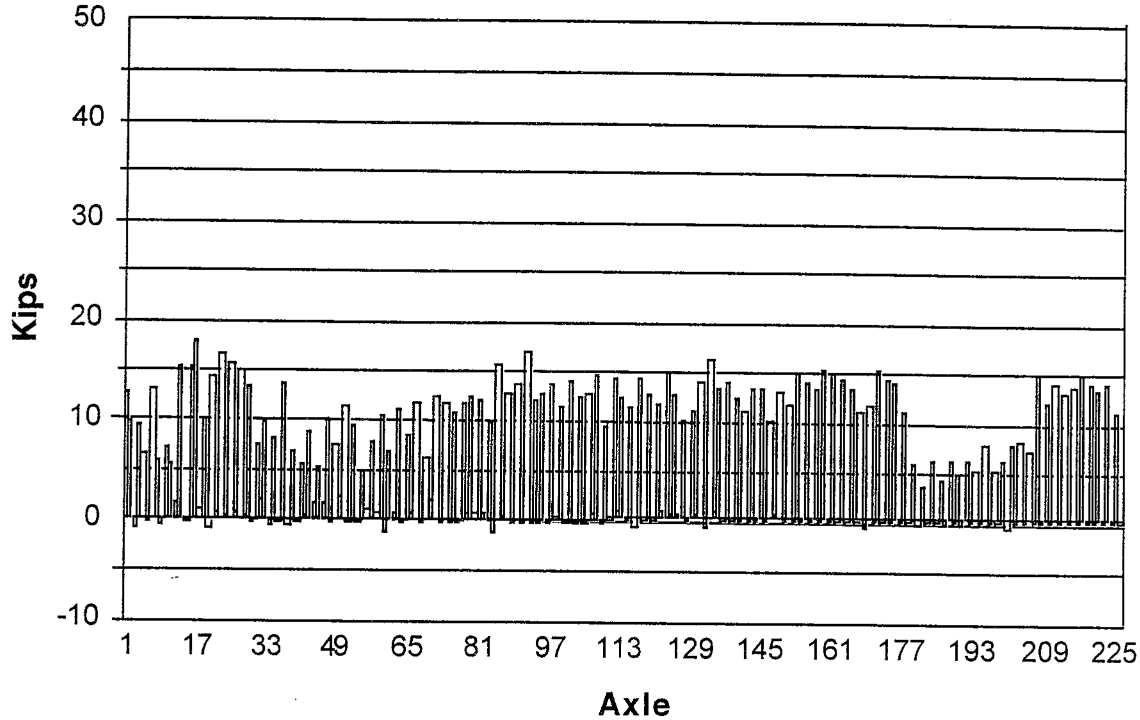


Figure 6. Locomotive Consist Electrical Output — Top-of-Rail



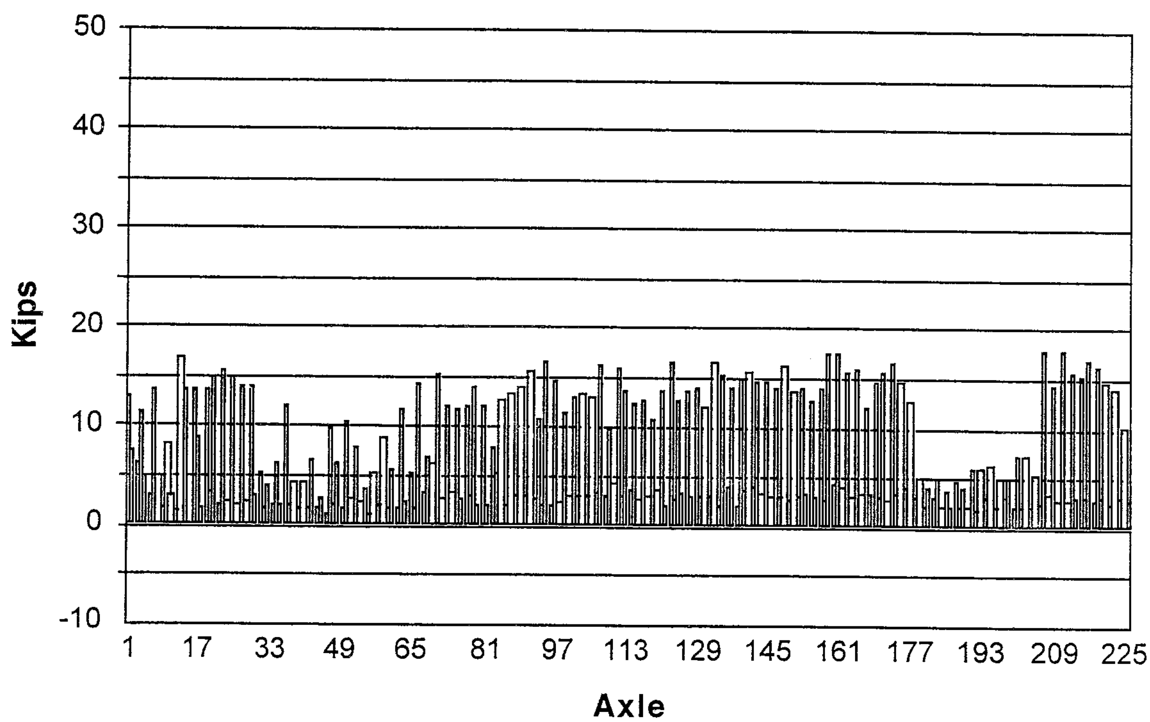


Figure 7. In-Train Lateral Forces, Dry Rail — 7.5-Degree Curve

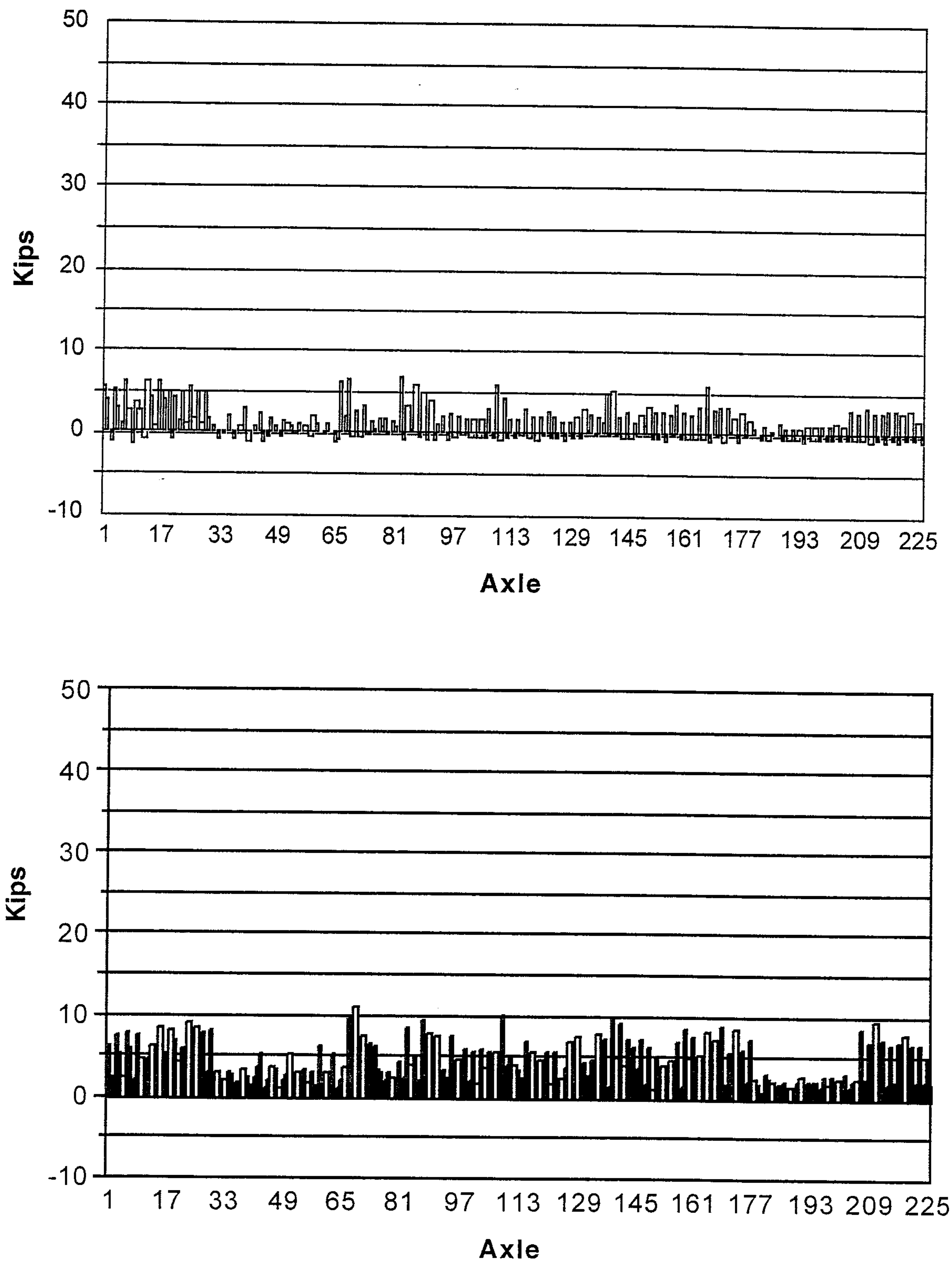


Figure 8. In-Train Lateral Forces, Lubricated Rail (TOR) — 7.5-Degree Curve

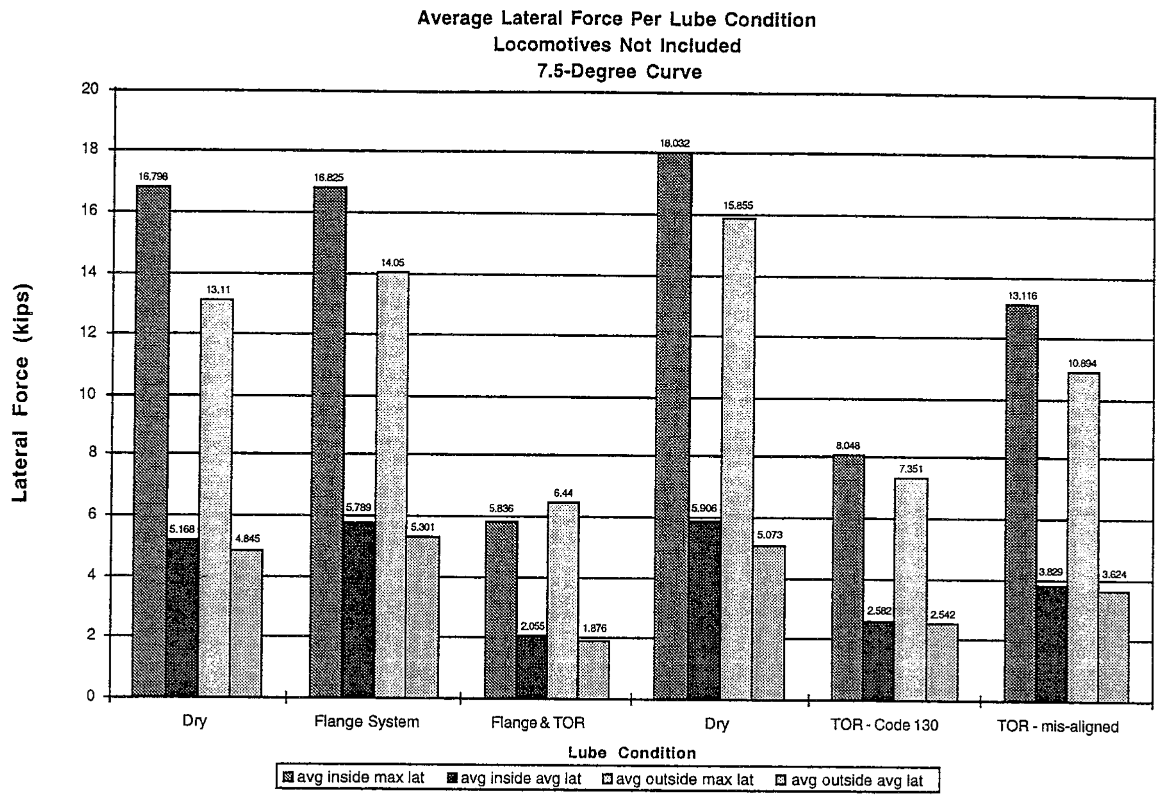


Figure 9. 7.5-Degree Curve Lateral Load Plot by Train Pass

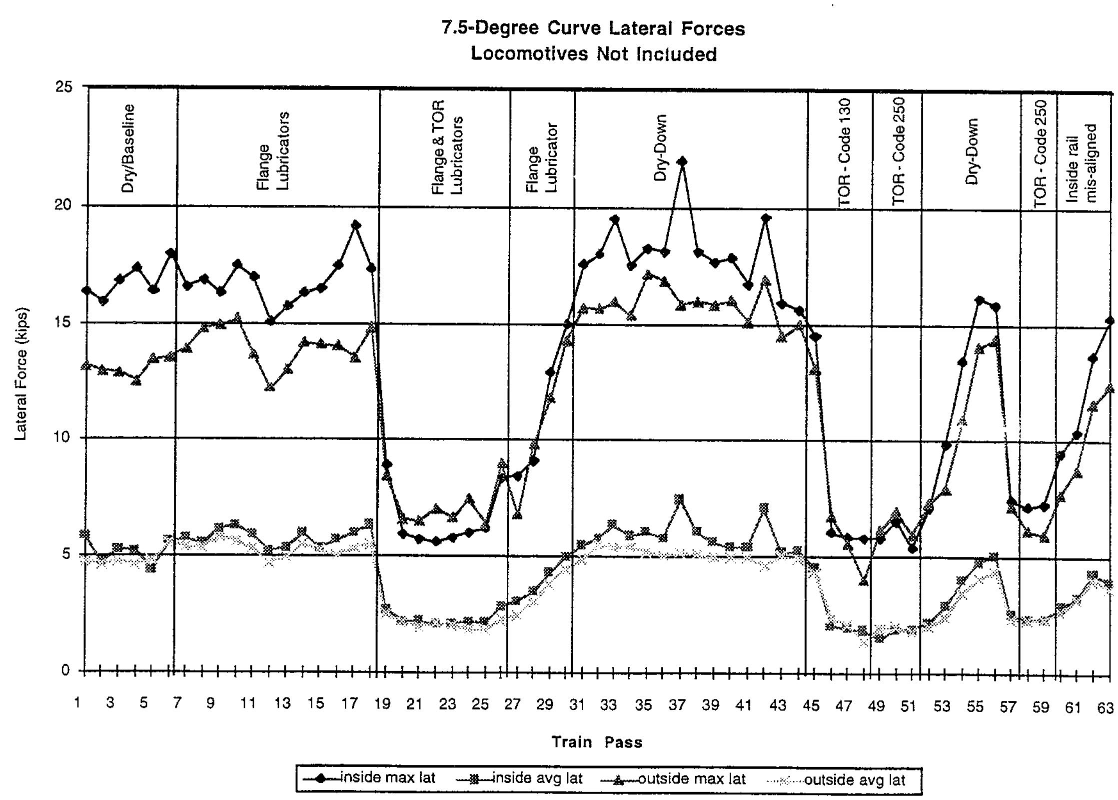


Figure 10. Average Lateral Forces — 7.5-Degree Curve

Table 3. Tribometer Log

Tribometer Readings for June 05, 1997				
Lube Condition	Curve	Top High Rail	Gage Face	Top Low Rail
Baseline	3	.50	.34	.49
	10	.50	.35	.47
	7.5	.58	.55	.59
	4	.58	.55	.59
Flange System	3	.26	.22	.35
	10	.25	.24	.32
	7.5	.49	.36	.52
	4	.45	.47	.47
Flange & TOR Systems	3	.24	.19	.27
	10	.26	.20	.25
	7.5	.35	.34	.38
	12	.33	.29	.33
Flange System	4	.39	.31	.33
	12	.34	.27	.30
Dry Down	3	.45	.29	.43
	10	.46	.45	.29
	7.5	.59	.42	.59
	4	.58	.38	.59
	12	.59	.32	.59
TOR System	3	.26	.25	.28
	10	.25	.20	.22
	7.5	.39	.46	.38
	4	.37	.38	.34
	12	.38	.35	.49
Dry Down	3	.38	.28	.34
	10	.45	.28	.44
	7.5	.48	.52	.50
	4	.58	.39	.55
	12	.55	.38	.58
TOR System	3	.24	.29	.29
	10	.22	.21	.27
	7.5	.40	.41	.42
	4	.39	.43	.38
Differential TOR	3	.25	.38	.23
	7.5	.40	.42	.56
	4	.37	.48	.58

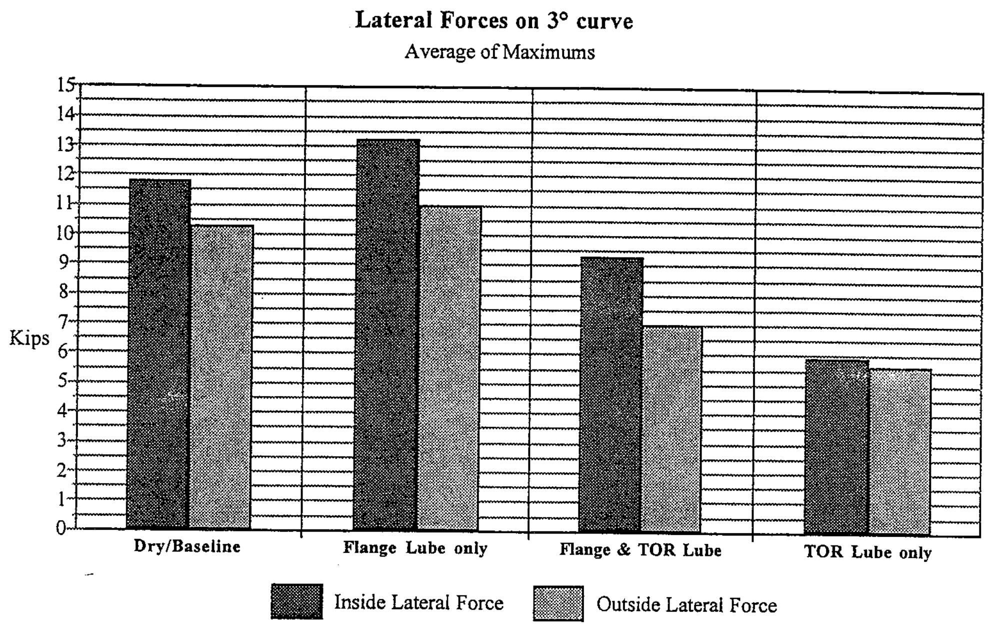


Figure 11. Average Lateral Forces — 3-Degree Curve

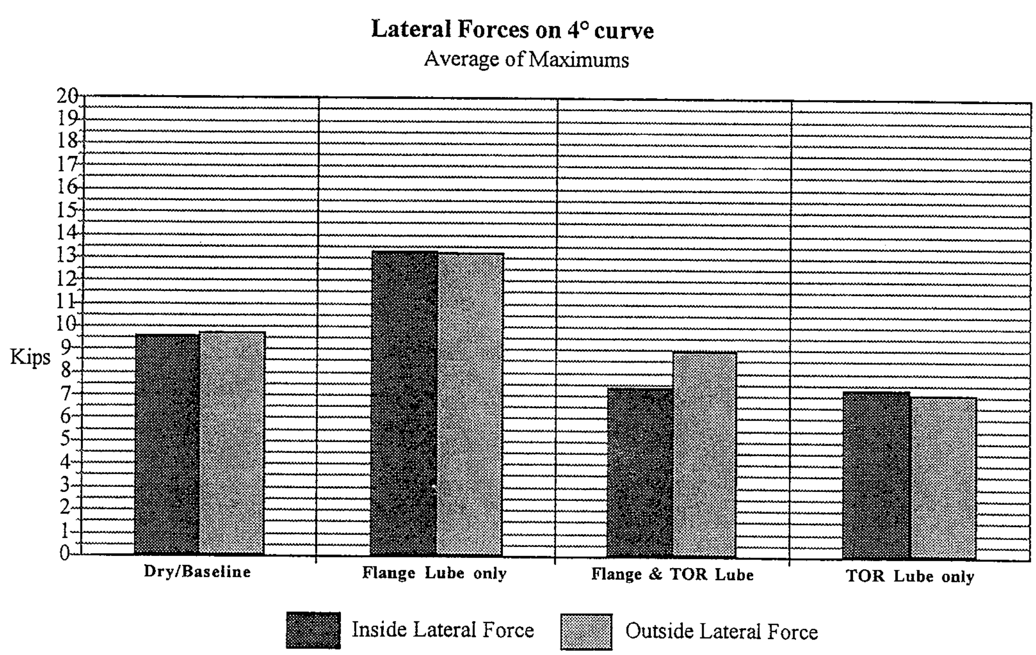


Figure 12. Average Lateral Forces — 4-Degree Curve

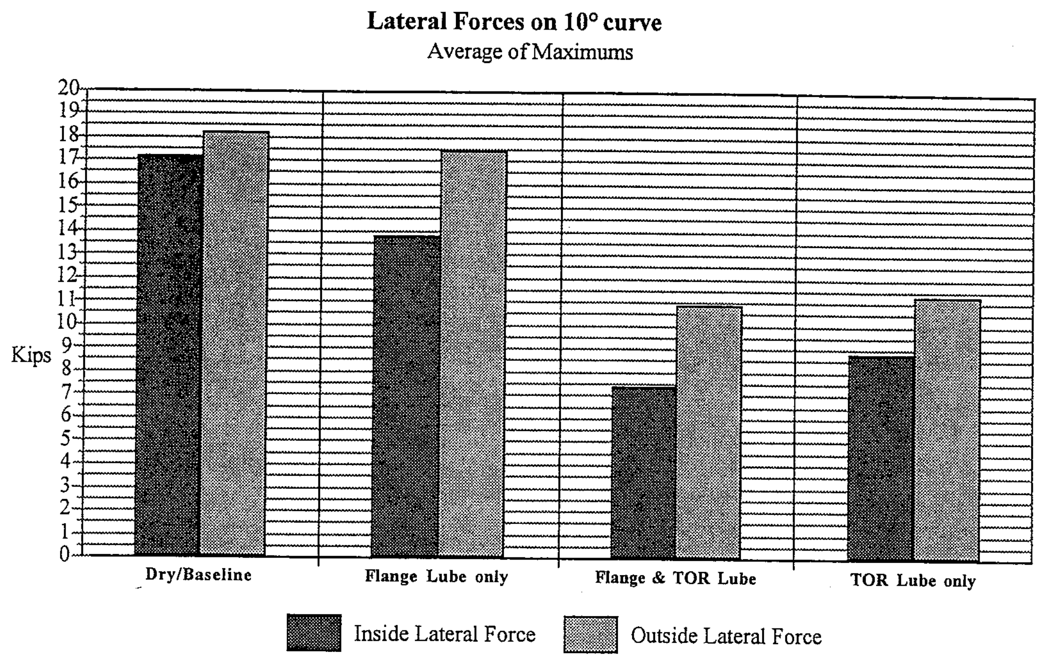


Figure 13. Average Lateral Forces — 10-Degree Curve

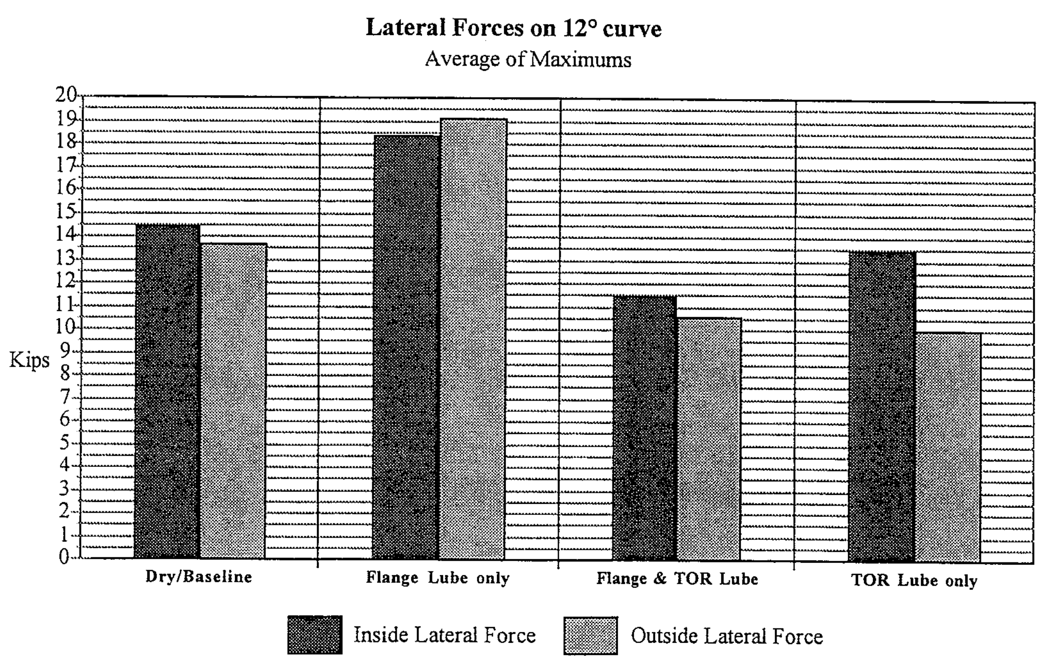


Figure 14. Average Lateral Forces — 12-Degree Curve

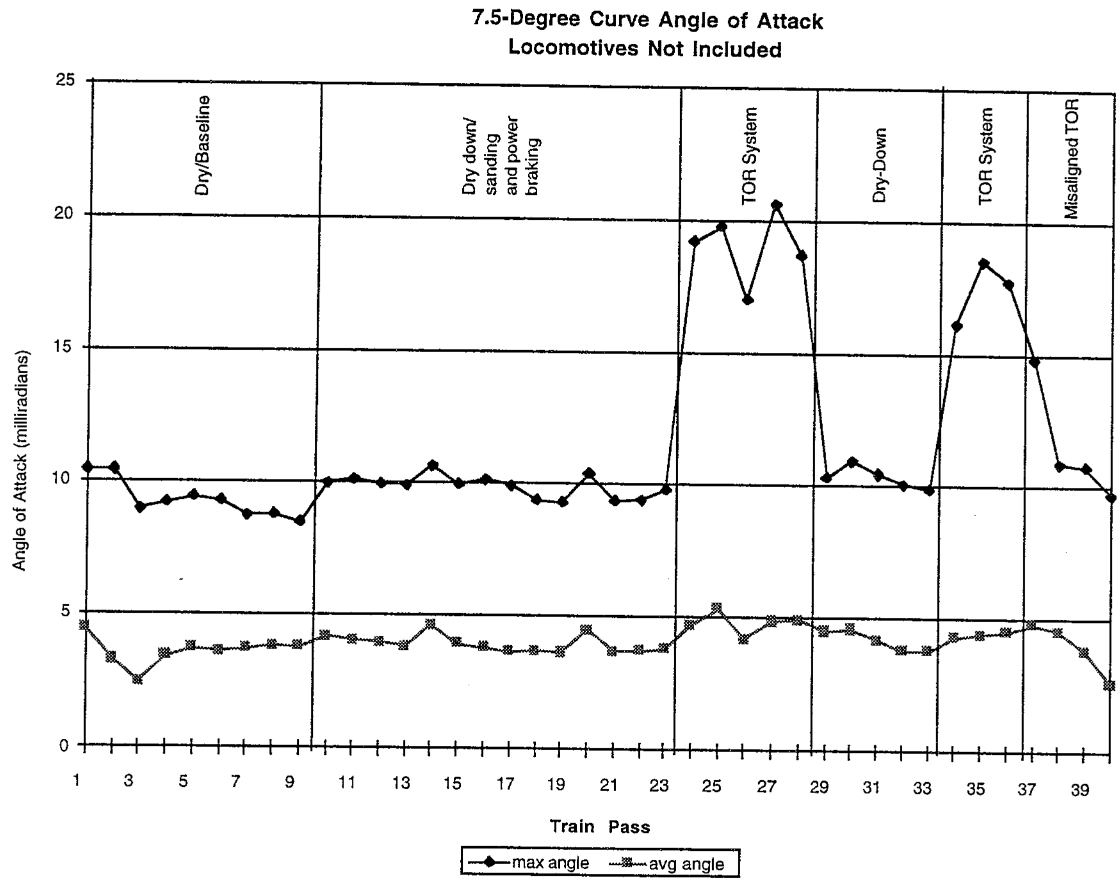


Figure 15. Lap History of Angle of Attack — 7.5-Degree Curve

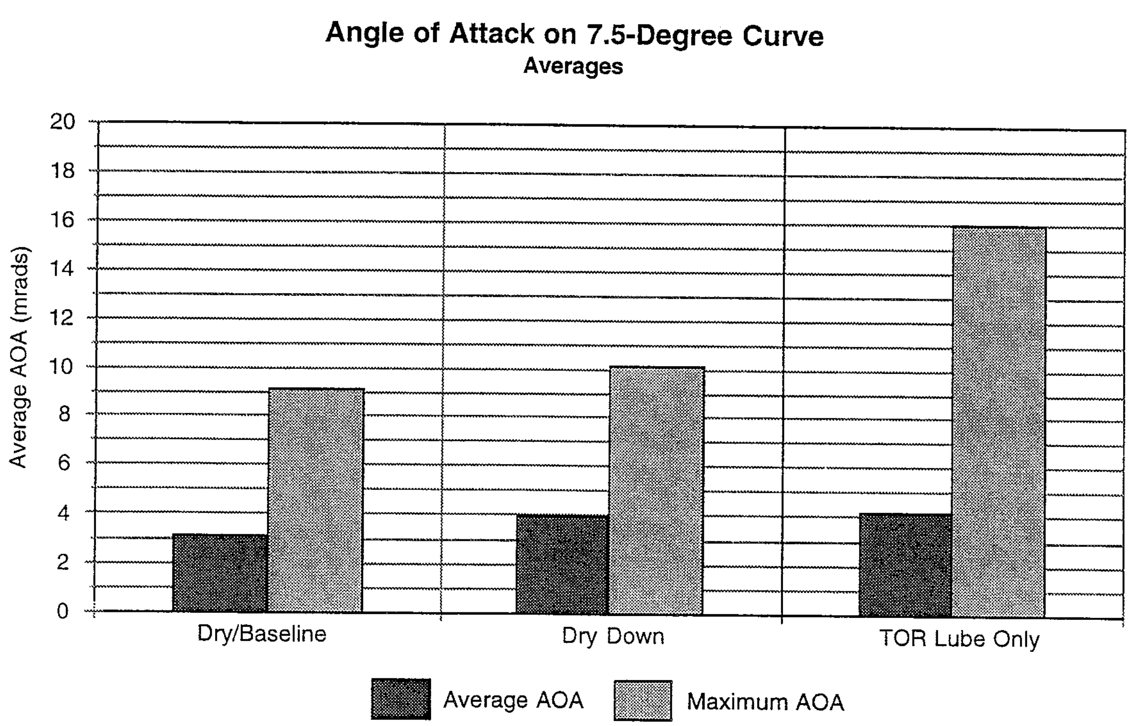


Figure 16. Average and Maximum Angle of Attack — 7.5-Degree Curve

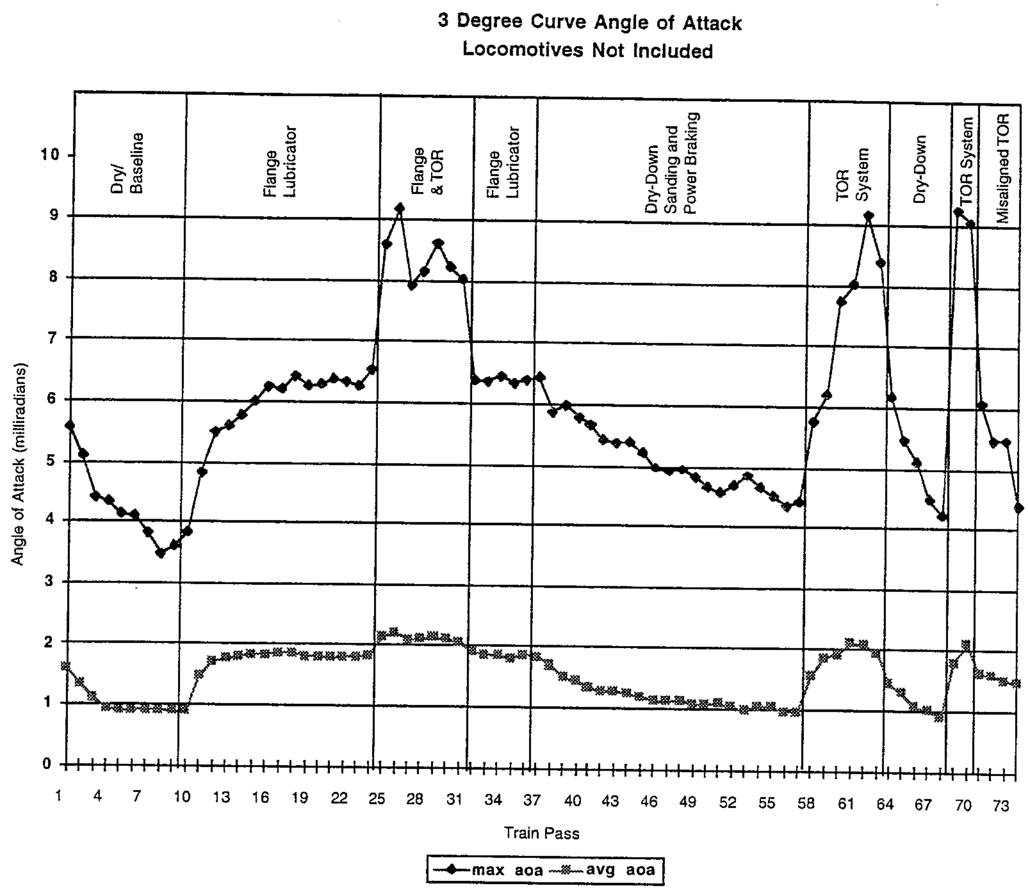


Figure 17. Lap History of Angle of Attack — 3-Degree Curve

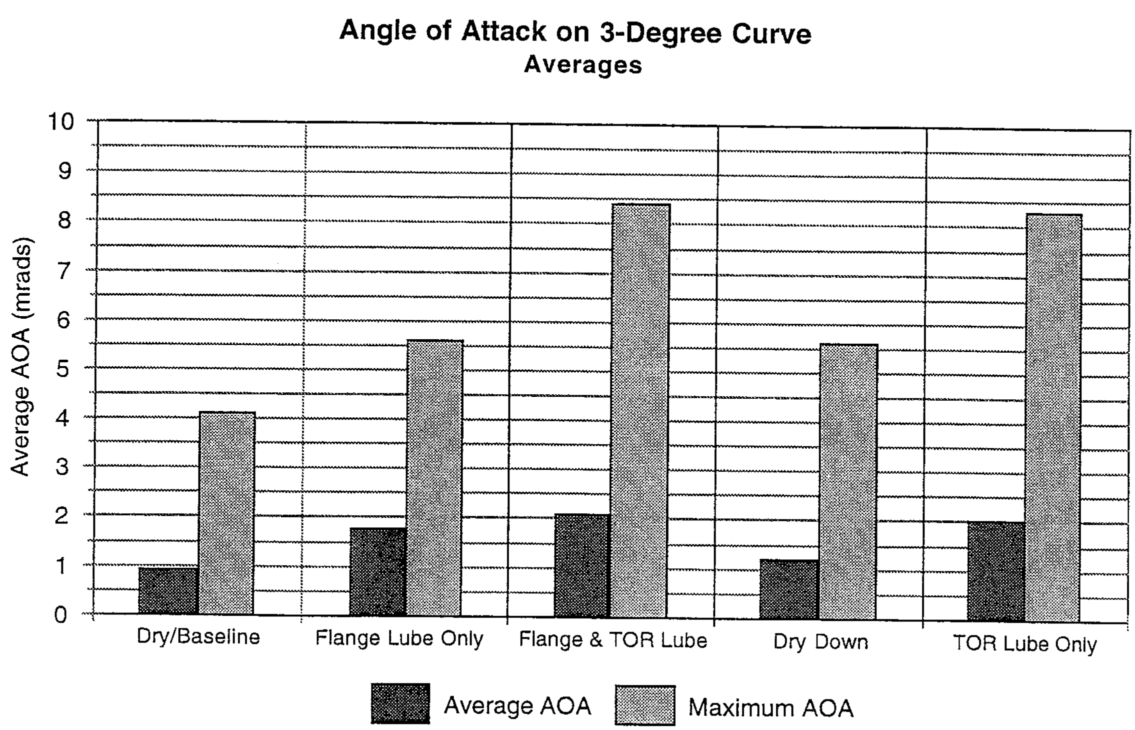


Figure 18. Average and Maximum Angle of Attack — 3-Degree Curve

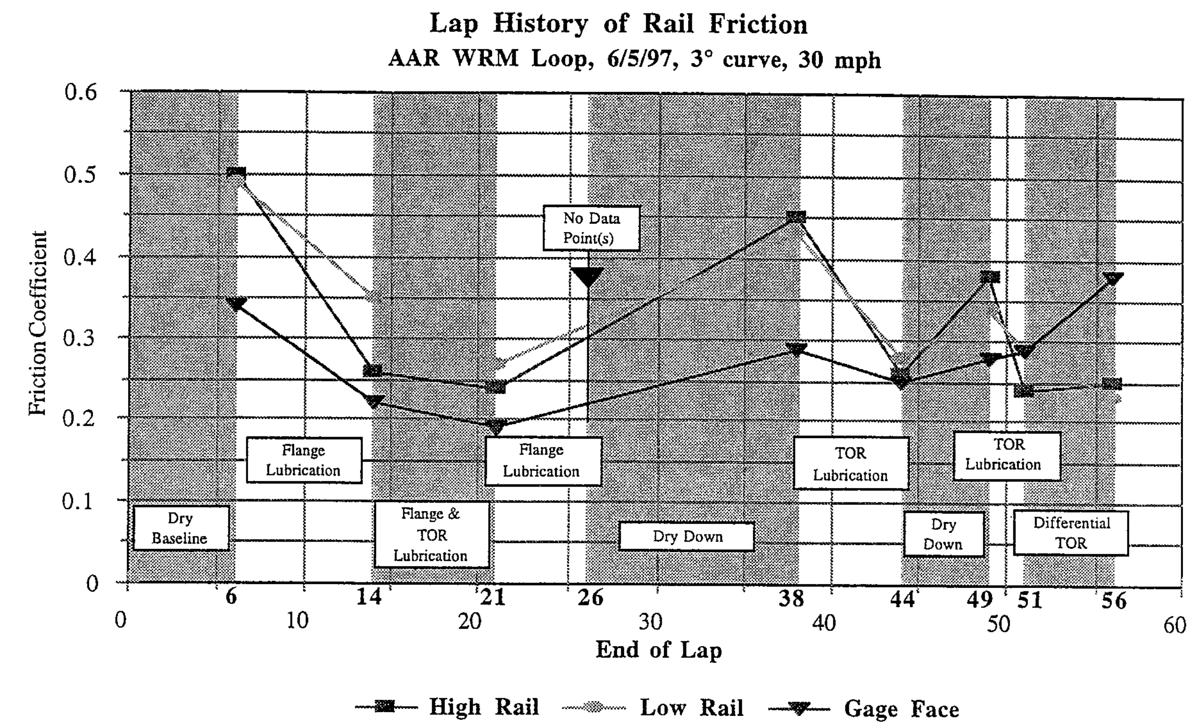


Figure 19. Lap History of Rail Friction — 3-Degree Curve

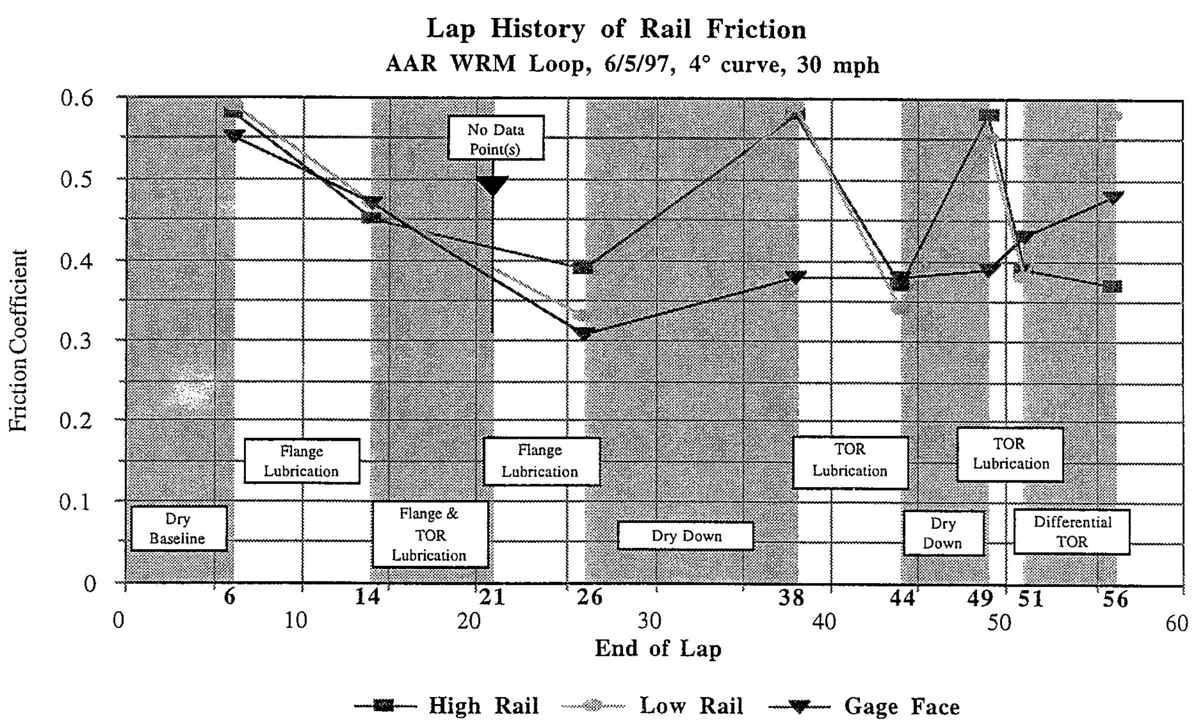


Figure 20. Lap History of Rail Friction — 4-Degree Curve

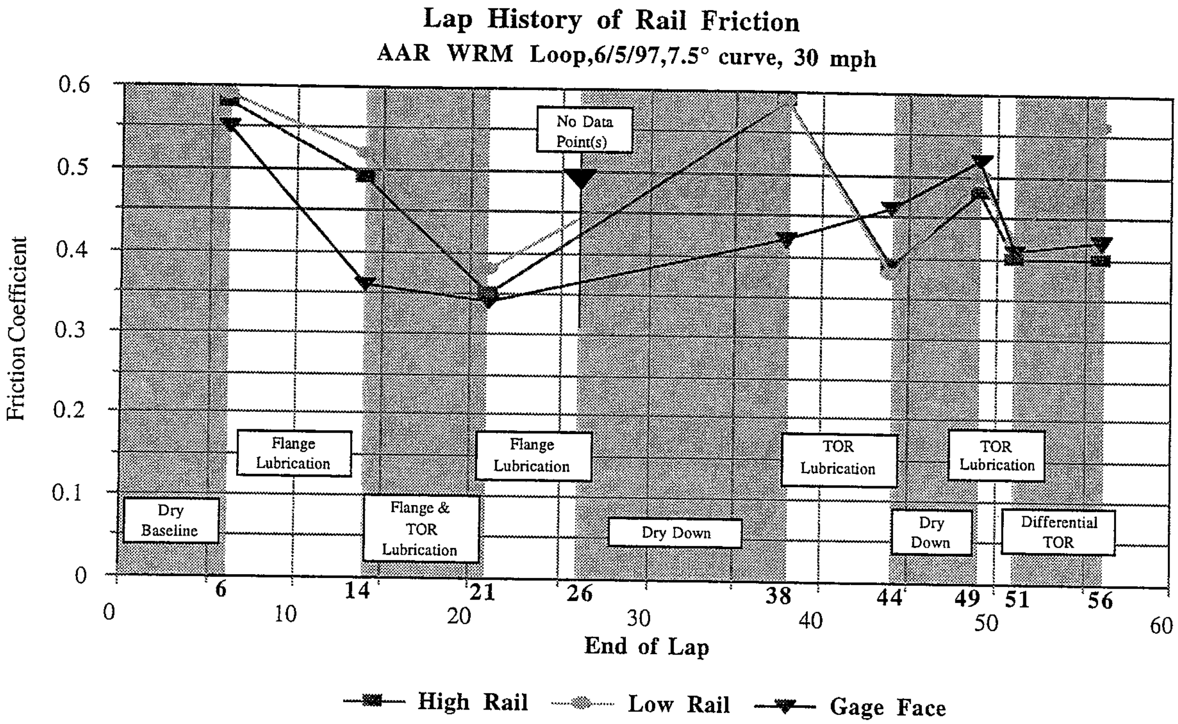


Figure 21. Lap History of Rail Friction — 7.5-Degree Curve

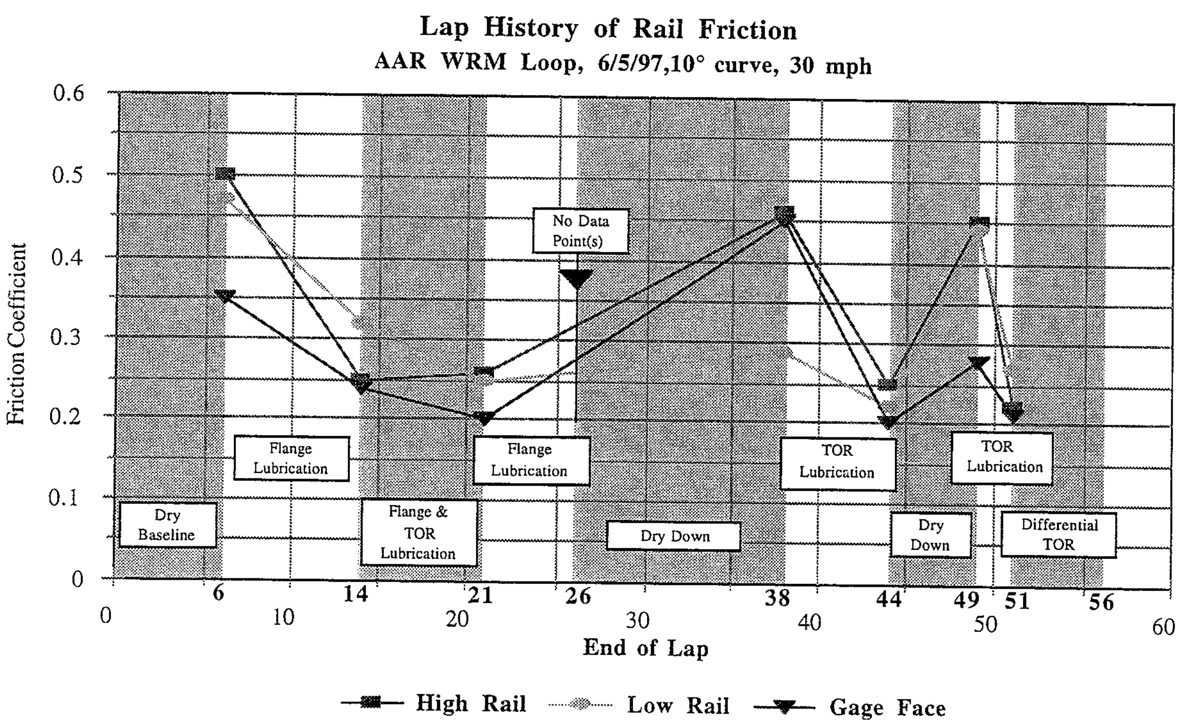


Figure 22. Lap History of Rail Friction — 10-Degree Curve

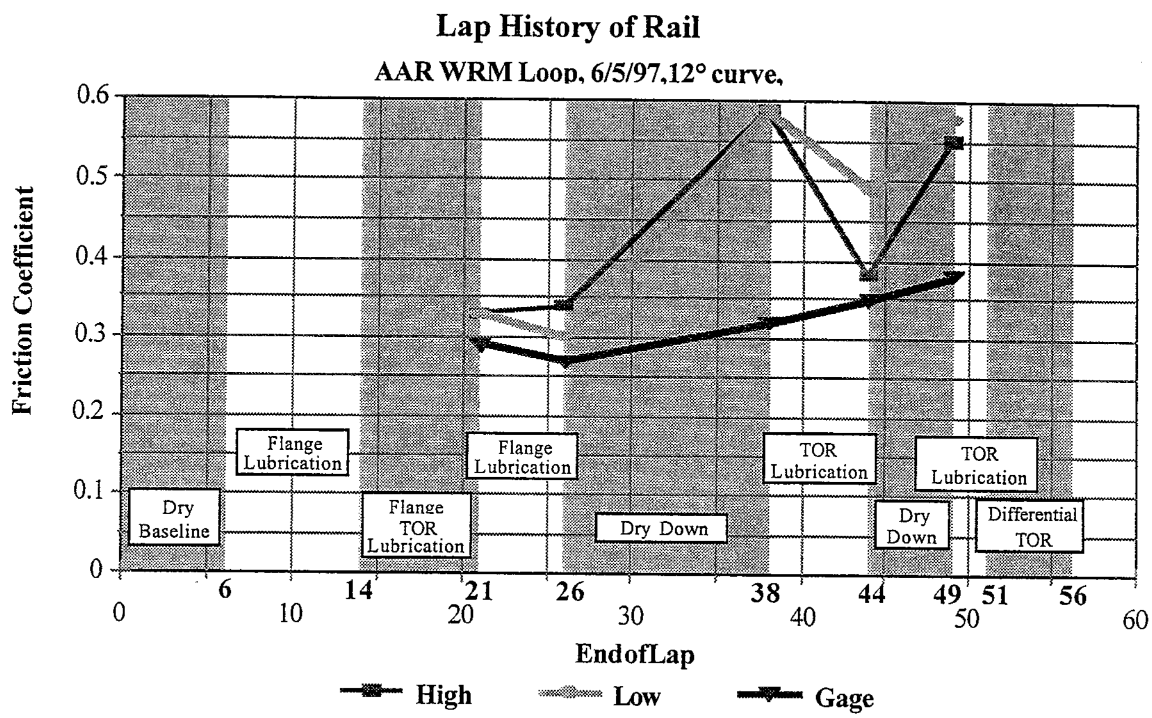


Figure 23. Lap History of Rail Friction — 12-Degree Curve

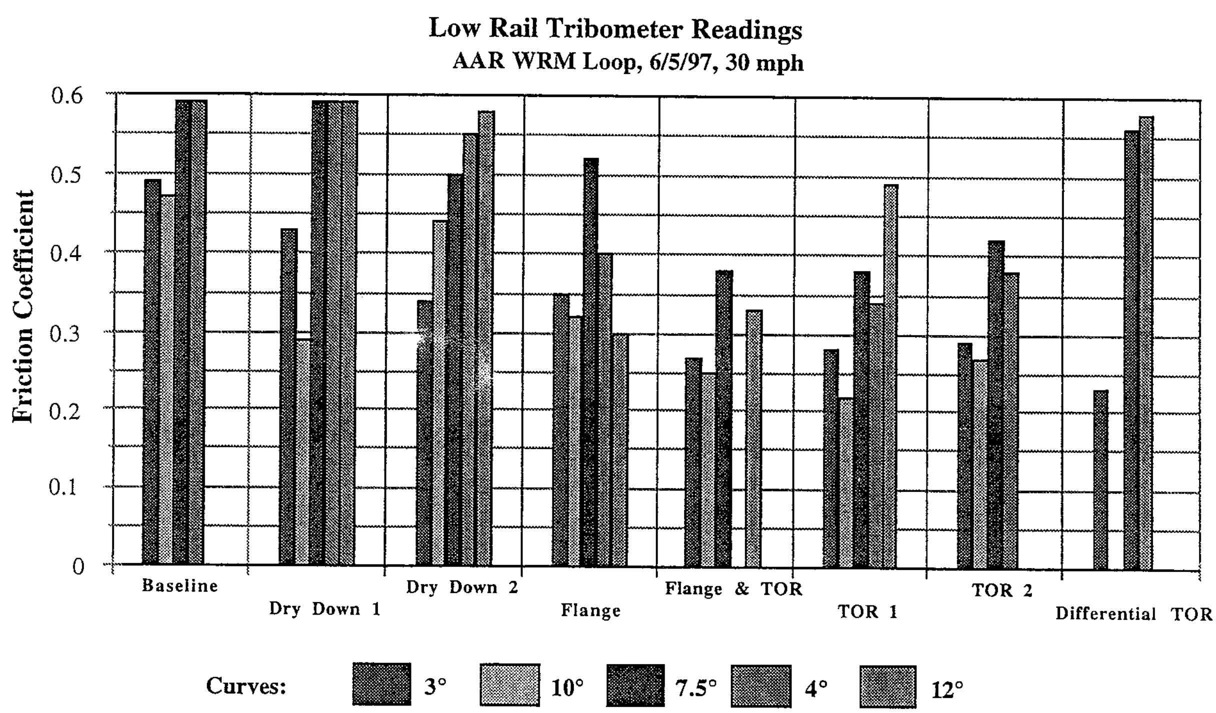


Figure 24. Top of Low Rail Friction — All Lubrication Patterns

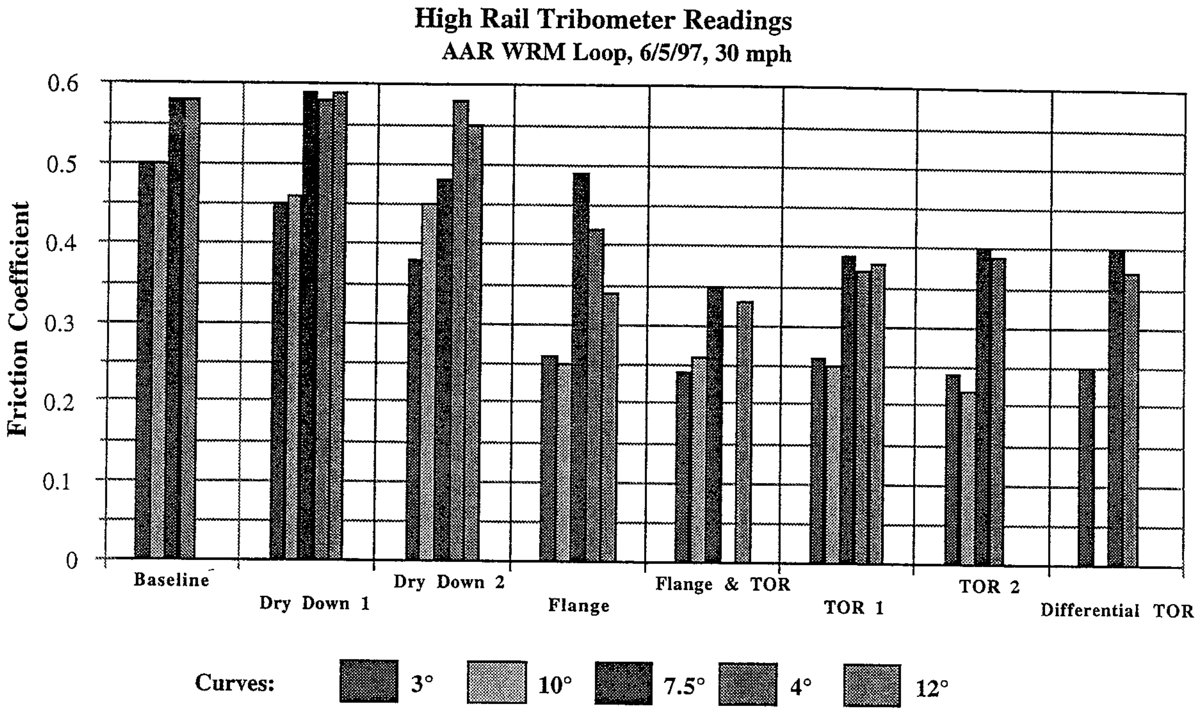


Figure 25. Top of High Rail Friction — All Lubrication Patterns

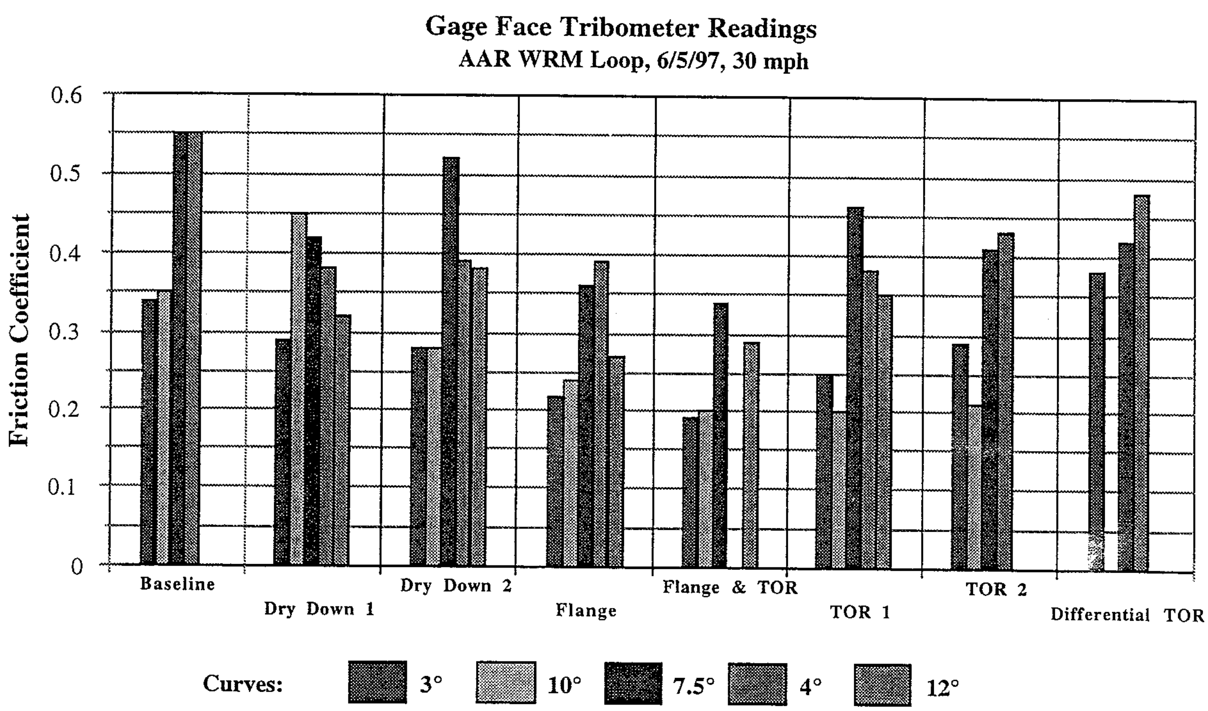


Figure 26. High Rail Gage-Face Friction — All Lubrication Patterns

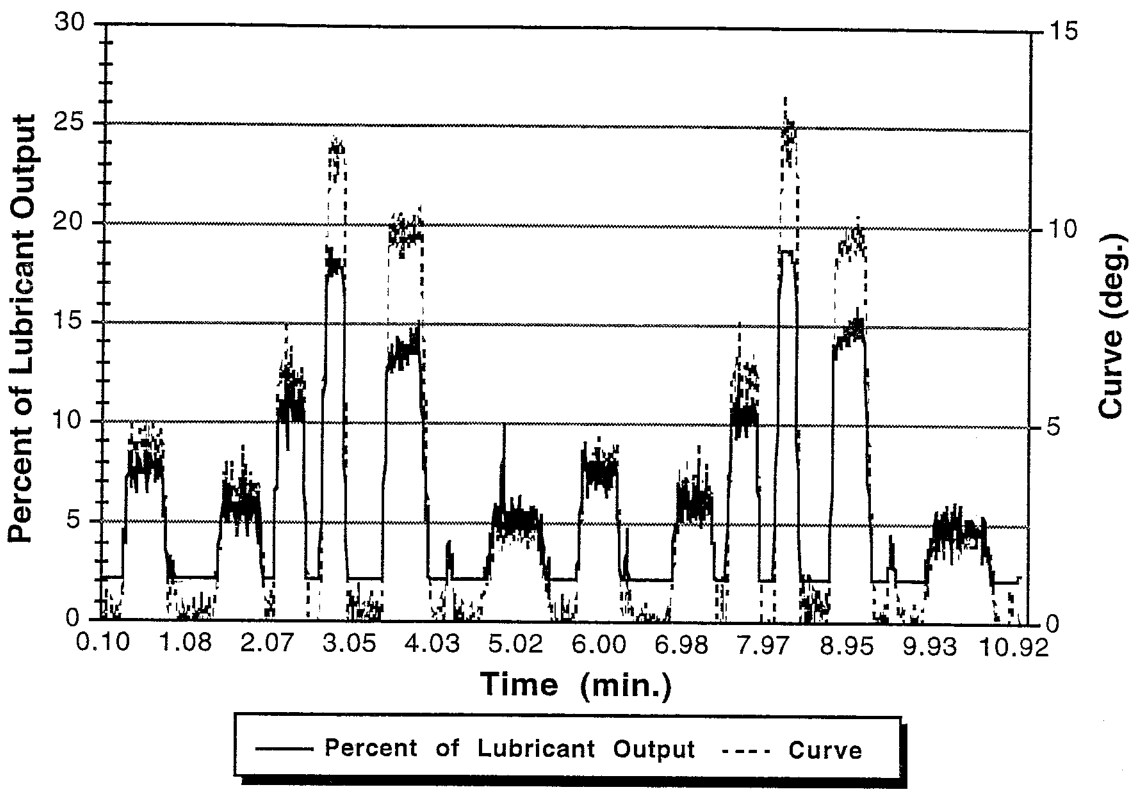


Figure 27. Curve Sensor and Percent of Lubricant Output by Time for Two Laps

The top-of-rail system, set at "code 78," was then turned on and combined gage-face and top-of-rail lubrication applied. An immediate drop in energy occurred; however, inspection of the rail by ground personnel indicated that gage-face lubrication that had migrated to the top of rail was mixed with top-of-rail lubrication being applied. Within a few laps after the combined application, the train crew reported wheel slip and the top-of-rail system was turned off. The top-of-rail system was then adjusted to a "code 130" but after one lap wheel slip was again noted. The top-of-rail system was turned off, while the gage-face system remained on. However the film on top of the rail did not rapidly disappear, and occasional wheel slip was still noted. The flange-only system was then turned off, at approximately lap 25.

The track was then dried down by operating the train with no lubrication system and some sanding and power braking. Energy levels started to increase, but after 10 laps of no application they did not return to the original dry-rail conditions. This indicates some residual gage-face lubrication remained and was not totally "burned off" during these dry laps. At this time it was decided to evaluate the top-of-rail system alone with the "code 130" rate. Wheel slip occurred on all locomotives during the third lap. This is demonstrated in Figure 6. After observing wheel slip, the vendor indicated that with a minor software change, an even lower rate "code 250" could be applied. Several additional laps (laps 36-41 on Table 1) were operated with these lower rates; however, wheel slip continued to occur, as highlighted in the boxes in Figure 2.

A brief dry down of the rail, which included sanding and power braking, was undertaken for several laps. Energy levels returned to close to the original dry values (Lap 53 of Table 1). One additional adjustment to the top-of-rail lubrication system was made by Tranergy with the code set to 250 as before. There was no wheel slip observed during the first three laps of operation. However, after the fourth lap wheel slip was noted and testing stopped. Additional dry-down laps were operated for the final test sequence.

The final test sequence was intended to determine the effect on lateral loads due to differential lubrication effectiveness as applied by damaged applicators. Such a condition might occur if one lubricator nozzle became misaligned but otherwise operated properly, thus one rail would receive more lubrication than the other.

Day 5 — June 6: The train consist was moved to the RTT track for evaluation of energy savings at higher speeds and on tangent instead of curved track. Initial laps were conducted under a dry condition to establish a baseline. However locomotive axle bearings became overheated and the test stopped. No additional operations were conducted.

4.0 DISCUSSION OF TESTS AND DATA

All tests on which data is reported were conducted on the 3.5-mile WRM loop. Every attempt was made to maintain the train speed within 30±0.5 mph. Data taken during laps in which this was accomplished was considered valid. Other data was discarded. In order to permit energy measurement in the whole lap, air-brake application was not permitted. The train braking was done by dynamic-brake application only. All the data gathered during the tests has been grouped in six different areas for this study: energy, wheel slip, lateral forces, angle of attack, rail friction, and accuracy of the system. Each of these is discussed along with the data given below.

4.1 ENERGY STUDIES

Energy was measured in three different ways: electrical traction energy, mechanical traction, and electrical and mechanical traction minus braking energy, for a quick look during testing only.

Electrical energy was determined by measuring the electrical voltage and current of the No. 2 traction motor of each locomotive. This is representative of the other five motors of each locomotive. Electrical traction energy was determined by ignoring the energy generated during dynamic braking, thus counting only the positive energy and not the negative energy. Energy produced during dynamic braking is wasted because this energy is dumped in the atmosphere through the heat radiated by the electrical grid of the locomotive to which this energy is supplied.

Mechanical energy was determined by measuring the force on an instrumented coupler behind the trailing locomotive in the locomotive consist. The constant to convert force to energy is:

1KWH = 502.681 lb. miles

thus,

(Force [lbs.]/502.681) x Speed (mph) x Time (hours) = Kilowatt Hours

For determining mechanical energy, computation of energy was made only when the coupler force was tensile or draft. When the force was compressive or buff, it was not included in the computation of energy.

The third form of energy measurement was used during testing and is a running total of both positive and negative energies added together. This results in the subtraction of the braking energy from the traction energy and can, therefore, misrepresent the energy savings when dynamic braking is used with standard diesel electric locomotion. For those countries operating electric trains which have the capability of returning regenerated brake power into the electric grid, it has some significance.

All the energy files reported here in data form are the electrical and mechanical traction energies. The term "locomotive energy" is also used for the electrical energy.

Figure 2 shows the locomotive energy and drawbar energy for all laps on Day 4 which contained "valid" train speeds. Laps where the train was started, stopped, or where speeds varied more than an average of 0.5 mph, were eliminated. Thus the train-speed variables have been eliminated, and back-to-back comparisons of energy under various lubricated conditions can be made. Figure 3 shows the percent reduction in energy from the dry baseline, with the exception of the blocks labeled "TOR from contaminated baseline." These percentages (23 percent and 22.7 percent) show savings of top-of-rail lubrication when compared to the contaminated rail conditions of laps 26-35, as shown in Figure 2 and summarized below in Table 3.

Table 3. Energy Savings as per Rail Condition

Rail Condition	Energy Savings From Dry
Dry	0%
Conventional Flange	19%
Top-of-Rail vs. Dry	30%
Top-of-Rail vs. Contaminated	23%
Top-of-Rail Plus Conventional Flange	30%

The third form of energy in which both positive and negative energies were added together were gathered in the form of summary data files. These are not reported here in any detail because of limited application to specific electric locomotive operations. The only issue worth noting is that the mechanical energy (drawbar) savings calculated was up to 44 percent by using the SENTRAEN 2000 system. This is one of the issues that should be evaluated in more detail in future testing.

4.2 WHEEL SLIP

Locomotive wheel slip should not be allowed to develop due to wheel or rail lubrication. After several laps, the recorded data shows that wheel slip developed for top-of-rail lubrication, and conditions similar to wheel slip were developing with flange lubrication. During top-of-rail lubrication, locomotive wheels slipped during dynamic braking on the 2 percent downhill grade and occasionally in traction. It should be noted that if the test mode permitted application of air brakes, wheel slip during dynamic braking may have been reduced or eliminated because the train would be slowed by braking torque on all train wheels (cars and locomotive) instead of braking only the locomotive wheels as was done in this test. Another factor that would contribute to better braking with air brakes is the wheel-cleaning action of the brake shoes.

Figure 4 shows the locomotive consist electrical output for dry rail. Note that there are no variations on any unit showing a drop of current in the flat line during dynamic braking or during the rest of the plot corresponding to traction. Figure 5 shows the effect of flange lubrication on electrical output of the locomotive. While there was no wheel slip on the lead locomotive during dynamic braking, the data shows that conditions of unloading similar to wheel slip were noted on the middle and trail locomotives.

The engineer could not have readily observed these conditions and therefore did not report wheel slip. Figure 6 shows the locomotive data after three laps of TOR–Code 130 and two laps of TOR–Code 250 (Figure 10). Wheel slip for all three locomotives can be seen. After the vendor made additional adjustments for reduction of lubrication rate and a rail dry-down, the second series of tests called TOR–Code 250 (Figure 10) showed no wheel slip in the first three laps (not shown here). There was no wheel slip in the fourth lap as reported by the engineer. Based on these observations, it is considered desirable to test again in the future with reduced TOR lubrication application rates.

4.3 LATERAL FORCES PRODUCED ON RAIL

Lateral forces produced on the rails in curves are an artifact of track and truck performance with which railroads must deal. When excessive, these forces can lead to derailment by rail rollover or wheel climb. These forces are a contributing cause of track damage and high costs of track maintenance. Lateral forces were reduced significantly by using top-of-rail lubrication whereas these forces actually increased when flange lubrication was used.

Figures 7 and 8 show lateral loads for inside and outside rails of the 7.5-degree curve, for dry and lubricated conditions, respectively for the entire test train. By comparing lateral loads for the dry (Figure 7) and top-of-rail lubricated (Figure 8) , it can be seen that both inside and outside rails have reduced loading. Note that the lower vertical and lateral loads near the end of the train were due to a block of 70-ton tank cars in the consist. Overall, there was a slight trend of reduced effectiveness of lubricant from beginning to end of train, as can be seen in Figure 8. However lateral loads at the end of train were significantly less than those created under dry-rail conditions, confirming that lubricant effectiveness had not been consumed by the end of the train. The reduced forces at the end of train were due to a residual amount of effective lubrication remaining after the last car passed. This residual amount of lubricant eventually resulted in a buildup and subsequent locomotive wheel slip.

Figures 9 and 10 show lateral load data collected at the 7.5-degree curve under a variety of lubrication conditions. Data suggests that dry and conventional flange lubrication results in the highest peak and average lateral loads. When only the top of rail was lubricated, the result was a significant reduction in lateral loads. The lowest lateral loads were observed when top-of-rail lubrication was mixed with flange lubrication.

Laps 55-57 were operated with the inside top-of-rail nozzle adjusted to miss the top of rail, creating a differential of lubrication. Lateral forces measured on the 7.5-degree curve increased from those with both rails lubricated, but did not increase to those noted under dry-rail conditions. These are shown for the 7.5-degree curve in Figure 6 and Figure 7. Testing was stopped after four laps due to wheel slip reported by the train crew. The remaining runs were to dry the track of all traces of lubrication, and energy data was not collected.

This data suggests that should one side of a top-of-rail lubricator become damaged or misaligned, and the other side remain in alignment and continue to apply lubricant, lateral loads increase and approach, but do not meet or exceed, those of dry and flange-only conditions. This data suggests that top-of-rail lubrication will decrease lateral loads. However, if one side becomes disabled, an increase in lateral loads from when both rails are lubricated will result.

The average maximum lateral loads for other test curves (3-, 4-, 10-, and 12-degree curves) are shown in figures 11, 12, 13, and 14. Note that under dry conditions, the 12-degree curve shows a lower lateral load than the 10-degree curve. This may be due to the nature of the 12-degree curve — it is the only reverse curve on the WRM loop, and truck warp may affect these loads under dry conditions.

4.4 ANGLE OF ATTACK

Angle of attack (AOA) is the angle that the wheel rolling direction makes with the rail direction. All conventional three-piece trucks commonly used by railroads can develop large AOA under normal service. Although this is undesirable, these trucks continue to be most popular because they are inexpensive to produce and maintain, have given good service since the 1930s, and have great vertical load equalization capability. For normal operation, increasing AOA is associated with increasing magnitude of lateral force on the rail. These forces are produced due to friction between the top of rail and the wheel tread. Production of high lateral forces makes excessive AOA very undesirable for normal operation. It should be noted that with the top-of-rail lubrication system, although the maximum AOA increased, the lateral forces produced on the rail decreased significantly. If the AOA increases much above 30 mrad there would be a concern for the potential of increased chance of flange climb at a misaligned joint, a frog, or a switch point due to high angle of attack.

Another undesirable feature that is normally associated with increasing AOA is the development of truck warping. This is caused by a twist moment that is produced by the large lateral and longitudinal slip or creep forces between the wheel and rail. It appears that with the top-of-rail lubrication system this twist moment is reduced, as lateral forces did not increase. Excessive AOA is detrimental in normal operation and normal friction levels because of:

- Increased wheel rail wear
- Truck warp which may lead to increased truck wear
- Warped trucks staying warped on tangent track, causing increased tangent rolling resistance
- Increased potential for derailment

The angle of attack on a given curve can increase in two ways. These are rigid-body rotation and truck warp.

Rigid-body rotation of the truck can develop between the rails because of an available clearance of .75 to 1.5 inch between the wheel sets and the rails. This clearance is larger for worn wheel flanges and worn rail-gage corners. AOA developed by rigid-body rotation can be up to 25 mrads on sharp curves.

Truck warp develops due to a twist moment experienced by the truck. This twist moment is produced by the creep forces generated between the contacts of the wheels and rails. AOA generated in normal curving is up to 20 mrads in curves up to 5 degrees. Truck warp can increase these values by an additional 10 to 15 mrads on the lead axle and make the trail axle run at a large AOA as well.

Increase of AOA up to 10 mrads was observed for a few bad-acting cars when top-of-rail lubrication was used. This angle-of-attack increase could be due to rigid-body rotation of the trucks. Since the friction-creep forces have been dramatically reduced, the contribution of rigid-body rotation towards increase of angle of attack is likely to be large. However, it cannot be so stated unequivocally without measurements, and future testing should therefore include measurement of truck warp for a few selected trucks.

Angle-of-attack data was collected in the 7.5-degree and 3-degree curves. The angle-of-attack history and averages for each condition are shown in figures 15, 16, 17, and 18. Data for operations during the "flange-only" and "combined top-of-rail and flange" lubrication operations at the 7.5-degree curve is not available, as the data-collection system (computer) failed during these laps. Similar data was collected at the 3-degree curve site. For laps where both databases are available, they show a similar trend.

A brief examination of the 3-degree data (figures 17 and 18) shows that AOA between dry and conventional flange lubrication results in a moderate increase in angle of attack, while top-of-rail lubrication increases the angle of attack even more. Peak angles of attack show an even higher effect due to top-of-rail lubrication. The 7.5-degree AOA data (figures 15 and 16) is described to allow comparison with lateral load data also taken at the 7.5-degree site (figures 9 and 10). Data suggests that the average angle of attack of passing cars is increased by a small amount with top-of-rail lubrication, with average angle of attack from dry to top-of-rail lubricated increasing from 4 to 5 milliradians.

However, some cars which exhibited "bad actor" characteristics, indicated a significant increase in both lead-axle and trailing-axle angle of attack due to top-of-rail lubrication. When top-of-rail lubrication was in place in the 7.5-degree curve, lead and trail peak angle of attack increased from an average of 9 milliradians to 19 milliradians. Examination of axle-by-axle values shows that both lead and trail axles of a truck were increasing. In both curves, when one top-of-rail applicator was disabled the angle of attack decreased. The reason for the increase of attack should be investigated in the future.

Examination of the AOA raw data shows the same cars generally repeated these high angles of attack for all passes when top-of-rail lubrication was applied. The high angles of attack occurred in the block of hopper cars received from revenue service, many of which contained representative typical "worn" trucks. The AAR was not able to document wheel and truck conditions of these cars prior to returning them to revenue service.

4.5 RAIL FRICTION

For the top-of-rail lubrication concept to be feasible for revenue-service applications, it is important to maintain a good friction level on the rail crown after the train has passed. This is important for developing good adhesion levels for the locomotives of the following train.

It was observed that for both flange lubrication as well as top-of-rail lubrication, the friction level decreased as compared to clean, dry baseline readings. This indicates the flange lubricant was creeping on top of the rail as has been observed by many railroads. The friction level for top-of-rail lubrication was in the same range (0.25 to 0.4) as for flange lubrication. After reducing the top-of-rail lubrication level below the present levels so that no residue is left on the rails, tests should be done to measure the new friction levels on the railhead.

Rail friction was measured using a hand-operated tribometer. As the measurement wheel can only determine friction at one location on the railhead (top, gage corner, gage face) at a time, multiple readings are needed, thus not all train passes could be measured. Table 3 summarizes rail-friction data collected during Day 4. Figures 19, 20, 21, 22, and 23 show the lap-by-lap history of average rail friction for each lubrication scenario for the 3-, 4-, 7.5-, 10-, and 12-degree curves, respectively. Figures 24, 25, and 26 summarize top of low rail, top of high rail, and gage-face high-rail friction for each condition and curve.

4.6 ACCURACY OF OPERATION OF SENTRAEN 2000

SENTRAEN 2000 uses several real-time inputs for computing the quantity of lubricant to be applied to the rail. One important input is the curvature of the rail. It was seen from the SENTRAEN 2000 computer output that it performed the task of tracking the curves and changing the lubrication output accurately.

Figure 27 shows the relationship between lubricant output (during top-of-rail tests — code 130) and curvature. Two consecutive laps are shown, and the repeatability of output and measured curvature can be seen.

5.0 CONCLUSIONS AND SUGGESTIONS FOR FUTURE TESTS/EVALUATIONS AND DEMONSTRATIONS

Data from this limited closed-loop demonstration suggest that top-of-rail lubrication can significantly reduce requirements for train energy while also reducing lateral curving loads. However, the steady-state application rate and corresponding energy savings that would be implemented in revenue service could not be validated or demonstrated during this test. Top-of-rail lubrication, while reducing energy and lateral forces, appears to result in an increased tendency of bad-acting trucks to increase angle of attack. Lateral loads were simultaneously reduced. Additional evaluations of the effects of high angle of attack on the transition to tangent track, truck-component wear, and the effect of hollow-worn wheel treads should be conducted. Further evaluation of these issues as they relate to top-of-rail lubrication application systems is recommended, but only after an acceptable lubricant-application rate, that does not lead to wheel slip, has been demonstrated.

Either the amount of lubricant and/or lubricant characteristics could be altered to eliminate the effects of residual films after the end of train. Presently Tranergy personnel are evaluating reduced amounts of lubricant to eliminate the residual film observed during TTC demonstrations.

Other field tests have been conducted with Tranergy top-of-rail lubrication systems, but only one train was equipped with the system. Following trains (those not equipped with top-of-rail applicators) tended to wipe the rail clean and no film buildup or wheel-slip problems have been reported. The closed-loop TTC tests simulated a railroad operation in which every train was equipped with a working top-of-rail system. These application rates and test conditions resulted in a gradual buildup of lubricant.

The concept of "behind-the-locomotive, top-of-rail" lubrication appears to have significant potential for revenue-service application if end-of-train carry-over can be controlled. It is recommended that further laboratory and closed-loop testing be conducted to better tune lubricant application and "consumption" rates to prevent unwanted buildup behind successive trains. The energy savings under these revised application rates could then be compared to that of other systems. This system's performance would be evaluated for its ability to reduce energy consumption, lateral loads, and angle of attack, along with its effects on train braking and hunting. These tests would be conducted over both curved and tangent track.

6.0 ACKNOWLEDGMENTS

This demonstration and evaluation was conducted with the cooperation of a number of railroads and sponsors. Financial sponsorship was provided by DOE and FRA which provided project funding for train operation, logistics, data collection, and reporting. AAR funds were utilized for a portion of the wayside data-collection and reporting efforts. Significant cooperation and coordination was provided by several AAR member railroads which supplied equipment and transported cars and locomotives to the TTC. The Norfolk Southern provided the three SD60 locomotives for use during this test, while cars for the trailing tonnage were provided by the following railroads: Burlington Northern Santa Fe, Union Pacific Railroad, Illinois Central Railroad, Canadian National, Canadian Pacific, and Kansas City Southern. Member railroads also provided valuable input and suggestions to the test plan, and sent representatives to the TTC during testing to observe and participate.

The test team during TTC evaluations was staffed by Tranergy, KLS Lubriquip, and AAR personnel. Special recognition is given to Mr. Vini Dyavanapolli and Mr. Kevin Voights of Tranergy for their assistance during the test period and for post-test processing of data. KLS Lubriquip personnel participating in the test were Mr. Lee Goldson and Mr. Dan Dicka. KLS Lubriquip also provided the locomotive flange lubrication system and assisted in its operation. Mr. Steve Luna of the AAR created the data-collection and analysis programs utilized in this test. Mr. Gene Woy of the AAR assisted in installation of instrumentation and data collection during all phases of the test.