Friction Control Methods Used by the Transit Industry

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 71

Track-Related Research

Volume 4:

Friction Control Methods Used by the Transit Industry

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), *Transportation 2000*, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, The National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

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The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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FOREWORD

By Christopher W. Jenks
TCRP Manager
Transportation Research Board

This report includes the results of a research task carried out under TCRP Project D-7, "Joint Rail Transit-Related Research with the Association of American Railroads/Transportation Technology Center, Inc., Friction Control Used by the Transit Industry." Information is provided on a variety of onboard and wayside friction control applications used in a transit environment to reduce noise, reduce wheel and rail wear, control truck steering forces, and reduce train energy. Descriptions of these applications are provided, along with their most appropriate uses. Operational issues associated with their use are also discussed. The report culminates in the provision of guidelines for selecting various types of friction control technologies. This report should be of interest to engineers involved in the design, construction, maintenance, and operation of rail transit systems.

Over the years, a number of track-related research problem statements have been submitted for consideration in the TCRP project selection process. In many instances, the research requested has been similar to research currently being performed for the Federal Railroad Administration (FRA) and the freight railroads by the Association of American Railroads's (AAR's) Transportation Technology Center, Inc. (TTCI), in Pueblo, Colorado. Transit track, signal, and rail vehicle experts reviewed the research being conducted by TTCI. Based on this effort, a number of research topics were identified where TCRP funding could be used to take advantage of research currently being performed at the TTCI for the benefit of the transit industry. A final report on one of these efforts—Friction Control Used by the Transit Industry—is presented in this publication.

The transit industry uses a number of what was once routinely called "lubrication systems" to reduce noise and vibration and to control wheel and rail wear. Because many of these systems now use more sophisticated materials than greases, the industry now more often uses the term "friction control" to describe these systems. The goal of friction control is to produce a specific friction level at specific locations on the wheel or rail, rather than simply to reduce friction to a low level on the gage face. This goal requires a higher degree of system control, applicator reliability, and lubricant (i.e., friction modifier material) development.

Under TCRP Project D-7 Task 7, TTCI investigated various wayside and onboard friction control applications used in transit environments. This investigation included a review of available friction control technologies, materials, and their associated implementation issues. The research included surveys of nine rail transit systems and field reviews of several applications, including the drilled-hole method of application at TriMet in Portland, Oregon, and a top-of-rail, vehicle-born applicator on the New Jersey Transit's Newark Subway.

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TRACK-RELATED RESEARCH
VOLUME 4: FRICTION CONTROL METHODS USED BY THE TRANSIT INDUSTRY

SUMMARY

A multi-project, track-related cooperative research program was initiated under funding by the Transit Cooperative Research Program (TCRP) Project D-7. The goal of the project was to adapt for use by the transit industry research already being performed. Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), has been performing research on lubrication application systems for the Federal Railroad Administration (FRA) and the freight railroads.

The transit industry uses a number of what is routinely called "lubrication systems" to reduce noise and vibration and to control wear. Because many of these systems use more sophisticated materials than greases, the industry is incorporating more "friction control." Friction control can reduce or increase friction of the wheel/rail contact patch, resulting in changes to system performance. This report reviews many current methods used for friction control, including application technologies and materials, each offering specific advantages and disadvantages in terms of cost, reliability, coverage, and effectiveness in reducing rail wear and noise abatement.

While both wear and noise are of interest, noise reduction is a key item of concern in the transit environment. The most commonly used methods of noise abatement in the transit industry have been variations of wayside-based flange lubrication. Recently, new solutions incorporating various methods of top-of-rail (TOR) friction control have been introduced. Wayside-based TOR solutions are available that generally target one or two specific curves or that can be configured to target distances of up to 1 mile. Other methods, specifically those that are onboard-based TOR, are intended to target problems systemwide.

Wayside TOR systems are loosely based on conventional wayside flange lubricator technology. Many transit operators have selected TOR wayside (a.k.a. "trackside") friction control application because it offers a familiar and effective solution to manage wheel/rail-generated noise issues and because it can be targeted to site-specific areas sensitive to public opinion.

Wayside-based friction control systems control noise and use delivery mechanisms generally proven in both freight and transit environments. However, the lubricant/friction control material commonly used is relatively expensive when compared with grease. The improper use of wayside application systems can affect train operating functions

such as acceleration and braking, especially in cases where the application system is located near sites where such activities are likely to occur. Improperly adjusted lubricators in or near embedded track in roadways shared with motor vehicles and pedestrians can be a safety hazard due to a possible slipping/sliding danger when excessive material is dispensed.

Because most of the benefits are seen by track or field users (customers, nearby property owners, etc.), the use of onboard flange and/or tread systems to control friction has been successful at a limited number of properties. Such systems require (1) a complete buy-in by management and by operating and maintenance personnel and (2) training of personnel in order to spot defective or inoperative applicators. The onboard option has been especially suited to transit systems with a small number (usually fewer than 50) and a limited variety of vehicle designs. Flange lubrication using onboard applicators has been more commonly used to control wheel flange wear, and some operators supplement the gage units with TOR applicators for noise control. Several operators who investigated onboard systems dispensing liquid lubricants were dissatisfied with the amount of waste and fling of material and dropped the option of onboard delivery. Others have opted for solid stick materials. The most successful implementation of onboard, solid stick systems has occurred with custom designed application devices developed for a particular truck or car design.

Regardless of the friction control solution selected (onboard or wayside), inspection, adjustment, and repair of the application system are integral parts of the implementation. When the friction control system is used to control rail wear, periodic inspection of curves is essential to ensure that adequate lubrication is being applied. For noise control, feedback from vehicle operators is a first line of defense in detecting improperly operating application systems. This feedback is essential to reduce or eliminate complaints regarding noise and to avoid excessive application of friction control or lubricant material.

CHAPTER 1

BACKGROUND AND OBJECTIVE

A multi-project, track-related cooperative research program was initiated under funding by the Transit Cooperative Research Program (TCRP) Project D-7. The goal of the project was to adapt for use by the transit industry research already being performed. Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), has been performing research of lubrication application systems for the Federal Railroad Administration (FRA) and the freight railroads. By leveraging results from freight-related research, the goal is to optimize solutions for transit. A number of TCRP projects have been investigated under this arrangement, including materials for optimizing friction at the rail/wheel interface.

Freight railroads use various application methods and materials to adjust friction at the rail/wheel contact patch to reduce rail and wheel wear, control truck steering forces, and reduce train energy. These methods incorporate a range of applicator systems that, even when operated correctly, can distribute excess lubricant onto the ballast and underbody of passing cars. Generally, as freight service is more severe, the amount of lubricant applied is higher than typically required for transit operations, further increasing the difficulty of using unmodified systems for transit systems.

Recently, the use of friction modifiers, which either reduce or increase friction to a specific range, has changed how railroad engineers define “lubrication.” The goal of friction control is to produce a specific friction level at specific locations on the rail or wheel, rather than simply to reduce friction to a low level on the gage face. This goal requires a higher degree of system control, applicator reliability, and lubricant (i.e., friction modifier material) development; thus, railroad engineers have defined this process as “friction control” rather than simply “lubrication.” In the remaining sections of this report, lubrication will generally refer to reducing friction at the gage face, while friction control will generally refer to producing friction to a specified level on the top (or in some cases also to the gage) of the rail. Characteristics and development of materials engineered to produce specified friction are discussed in greater detail in Chapter 3.

For these reasons, unmodified versions of conventional gage lubrication systems require significant development before they can be favorably received in the transit industry. In some cases, such as the TOR concept, wayside applications were first designed for transit use, while early versions of mobile-based applications were developed for freight applications. In each case, variation in material, in application systems, and in the amount applied was required to obtain proper benefits. Additionally, the transit industry is especially sensitive to noise generated by passing trains (for both adjacent neighboring sites and passengers) and service disruptions for repair of track components. While rail/wheel lubrication has been used extensively in the freight railroad environment to reduce wear and to control curving forces, transit operators have been reluctant to apply widespread lubrication because of concerns about contamination (e.g., dirt, brake shoe dust, or excessive grease) and about creating unsightly conditions. In addition, rail lubrication for freight railroads has been optimized to address wear and energy concerns, leaving noise control as a secondary issue.

A major component of wheel squeal is lateral creep at the wheel/rail interface. Under certain conditions, lateral creep could lead to lateral stick-slip oscillations, which, in turn, may excite high-frequency vibrations in the wheel plate and rail. Demonstrations have been conducted where gage face and TOR friction had been controlled independently. At the majority of these sites, the greatest noise reduction was achieved when friction at the wheel tread and at the head of rail were controlled. Thus, controlling TOR friction is a viable method of reducing noise generated by rail/wheel interactions. Because gage face lubrication is more common and well understood by most transit operations, this report emphasizes methods for reducing noise by controlling TOR friction. The report also discusses attributes and implementation issues of recent innovations that have demonstrated significant improvement in interchange freight service situations.

CHAPTER 2

TECHNOLOGY DESCRIPTIONS

2.1 TECHNOLOGY OVERVIEW

A number of TOR lubrication/friction control technologies have been evaluated to address the transit industry's concern with rail/wheel interface noise generated by contact between the wheel tread and the head of rail. Some of these technologies were developed initially for transit applications, with the intent to modify them for freight railroad use. The following methods have been used to apply friction control materials:

- Dispensed from a wayside system,
- Dispensed from an onboard system,
- Delivered from a hi-rail system, and
- Applied by hand using brushes and rollers.

Each of these application systems has inherent advantages and disadvantages. Transit system size, track configuration, environment, and other issues must be assessed to determine the appropriate and acceptable application.

2.1.1 Wayside Systems

Because many noise issues are site-specific (often identified by complaints from the public), a majority of the transit operators prefer wayside systems as the most practical and cost-effective solution for their situation. Of the wayside TOR systems, various manufacturers offer two basic delivery/transfer design concepts: (1) modified wiper bars and (2) holes drilled in the rail. These materials differ in their approaches to lubricant dispersion, lubricant application, and the lubricant characteristics required for optimum effectiveness. Models from the main TOR lubricant system suppliers to the North American rail industry are in service among many transit operators in Canada and the United States.

2.1.2 Onboard Systems

Onboard systems are often used where systemwide friction control is intended. Instead of material being applied at wayside locations (thereby providing site-specific control of friction), applicators are installed on a large percentage of the car fleet, allowing the friction control material to be applied during normal operations. Although this application reduces or eliminates needs for wayside systems, a track configuration with variable severity or isolated problem areas may not receive adequate application at all locations, which may result in insufficient material at severe or critical locations.

Onboard systems for transit applications can use liquid or solid forms of lubricant and friction control materials. Liquid materials are held in reservoirs and are delivered to nozzles configured to apply the material to wheel flanges. In the case of friction control materials, the nozzles can also be configured to apply material to the wheel treads. Solid versions of lubricants (i.e., friction reduction) and friction control materials are also available. In such cases, the solid material is formed in a tube or stick configuration and is then rubbed against the wheel tread or flange. Material selection will depend on the need to decrease or provide a specific level of friction.

Regardless of the nature of the material being applied (liquid or solid material), the mechanical alignment of the applicator device is critical. Nozzle or applicator alignment is of extra concern when applying lubricants (rather than friction modifiers). Should misalignment of the applicator occur, some lubricant may be applied to the wheel treads, which could adversely affect braking performance.

2.1.3 Hi-Rail Systems

The use of hi-rail inspection vehicles to apply lubricants, and in some cases friction control materials, to the rail is a common practice among some freight railroads. This approach involves periodically applying a specific amount of material to the rail. This approach has not found widespread use in transit applications because hi-rail systems require an additional vehicle to operate over all sections of track. Track time between trains is greater on branch and secondary freight lines; therefore, this method has experienced more acceptance on such locations.

2.1.4 Hand Application

Friction patterns developed by either wayside or hi-rail methods can be produced in localized areas by hand application, which simply uses hand labor to wipe or spread lubricant. As in hi-rail application, this method also requires track occupancy or authority to obtain access to the rail. The ability of this method to obtain acceptable results is limited because effectiveness is generally observed only at or near the location of application. In many instances, hand application of a friction control material has been found to be effective (for localized issues) whereas installation of a wayside unit is difficult. Further, testing and evaluating various materials and locations for friction control is often initially done using hand application, which is then followed by implementation of an automated system. Proper operator training is essential to avoid over- or underapplication of materials.

Specific issues regarding wayside and onboard application systems are discussed in the following sections. This report concentrates on solutions observed that address noise control—a major issue for the transit industry. Hence, this report evaluates methods of controlling TOR friction in more detail than it evaluates conventional gage face lubrication systems.

2.2 WAYSIDE-BASED FRICTION CONTROL/LUBRICATION

Of the various lubrication methods and materials used by the freight railroad industry to reduce rail and wheel wear, to control truck steering forces, and to reduce train energy, the most commonly used is wayside based. This concept distributes lubricant (often a form of grease) on the rail, customarily on the gage face. For the majority of transit noise requirements, however, the need for friction control is on the TOR. However, wayside-based applications can also be configured to apply material to the TOR through the use of modified wiping bars that are mounted to the field side of the rail (instead of the gage side used by flange lubricators) or through the use of a hole drilled from the TOR to the web, allowing friction control materials to be applied directly to the railhead.

2.2.1 Wayside TOR Application Equipment

Wayside application equipment uses a variety of systems to power and deliver friction control materials to the desired position on the track, including mechanical, hydraulic, electric, and pressurized gas systems. The first three types of system use various means of activating a mechanical pump, while the pressurized gas system propels the lubricant to the desired location. For freight railroad applications, selection usually depends on the availability of power at the installation site. Transit applications require a much more refined control of application quantity. Thus, electric or, in a few instances, pressurized systems have found favor. The pressurized approach sprays passing wheels from a set location and has seen only limited application. For the more conventional pump-based systems (regardless of how the application system is powered or the nature of the friction control material), the material is delivered for TOR applications by one of two transfer mechanisms: through one or more small holes drilled into the railhead or, more commonly, through a single nozzle or a series of nozzles on a field side–mounted applicator bar. TOR applicator bars may be similar in appearance to gage face bars. However, their mounting and function are different and not interchangeable.

2.2.1.1 Pump Systems

Traditionally, pumps and lubricant/friction modifier reservoirs are housed in the same unit to facilitate adjustment and repair and to limit exposure of components between the reservoir and pump. Pumps can be activated mechanically, hydraulically, or electrically. Mechanical and hydraulic activation require direct contact between passing wheels and an actuator; therefore, they tend to require more frequent inspection and repair. Mechanical methods also offer less adjustment for output rates and are more susceptible to changes in material viscosity due to temperature variations. For new installations, and for upgrading existing locations, electric pumps offer a wider range of output control and are more uniform in output rate. However, they also require a power source (commercial AC power or battery/solar), a separate actuating sensor, and more sophisticated training for component repair.

Because the TOR application requires a very accurate amount of friction control material, the only acceptable method for depositing the material is using electrically operated pumps in place of mechanically operated pumps.

2.2.1.2 Pressurized Systems

One manufacturer uses a charged container of compressed nitrogen gas to deliver friction control materials. The lubricant/friction modifier reservoirs and gas bottle are housed in a steel cabinet mounted alongside the track. A vibration sensor, magnetic valve, and nozzle housing are mounted on the railroad tie, as shown in Figure 1. A 9-volt battery and nitrogen gas power the system, allowing it to be installed at sites regardless of electric power availability. There is no direct mechanical contact between the system and the rail or wheels, thereby reducing the wear on system components. Maintenance and service consist of lubricant/friction modifier refills and nitrogen gas bottle replacements. Service intervals depend on traffic density and may range from 2 to 12 months. In addition, the manufacturer recommends replacing the battery annually.

2.2.2 Delivery/Transfer Methods

Once the lubricant or friction modifier has been pumped, it must be delivered to the proper location. The reason for recent interest in TOR lubrication is that conventional gage face units do not control TOR migration with sufficient

Figure 1. Nitrogen gas–charged lubricant/friction modifier cabinet.

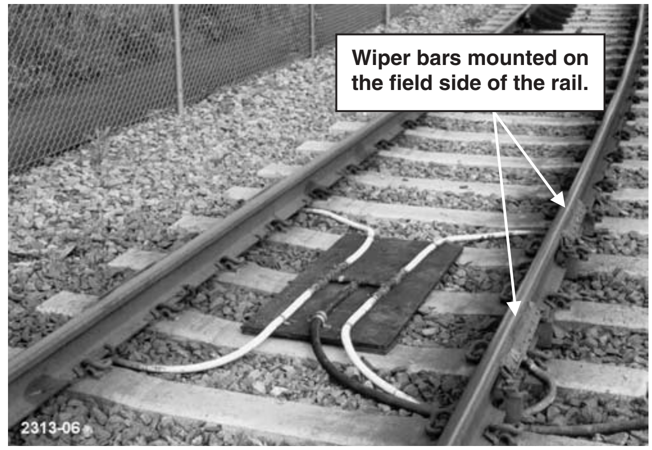

Figure 2. Typical wayside-based TOR wiper bar arrangement.

accuracy. If a system deliberately applies materials on top of the rail, the resulting pattern can be optimized to provide the required amount of material at the needed location. To address this need, two options exist: wiper bars and drilled holes.

Regardless of the applicator option selected, wayside TOR application devices must be located on track with no cross level (i.e., with zero superelevation) in order to be effective and reduce material waste. As the material is pumped to the TOR area for pickup by passing wheel treads, any superelevation will result in material running off the rail head before being picked up by passing wheels.

2.2.2.1 Wiper Bars

Of the two available methods of delivering friction control material to passing wheels, modified wiper bars have received the most use. Modified wiper bars have been used on transit sites and on freight railroads to deliver friction control materials to the TOR. These wiper bars look and function similar to conventional gage face wiper bars with the following exceptions:

- They are mounted to the field side of the rail.
- They are intended to deliver lubricant/friction control materials not to the flanges, but to wheel treads.
- They are mounted higher, with the top being even with the TOR.

Figure 2 shows a typical TOR wiper bar configuration on a transit application. Friction control materials are pumped into these bars and distributed along a distance of at least 2 feet, with the intent that the material migrates across the head and is picked up by passing train wheels.

An advantage of field side applicator bars is that multiple bars can be installed to allow materials to apply to the entire circumference of the wheel, which results in increased rail coverage and distance protected. Still, such bars are difficult to install in embedded track without removing large amounts of pavement or causing concerns of waste or contamination.

2.2.2.2 Drilled Holes

Drilled holes can be engineered to apply a material to an exact location on the railhead. For custom applications, the hole can be aligned to different locations. Figure 3 shows a typical drilled-hole arrangement on the embedded track of a transit system. The drawback of this option is that the hole cannot be easily relocated if the system needs to be moved, and changing the rail will require a new or replacement hole to be drilled. Although this concept is not new to the freight railroad industry (where it has seen limited use in yard tracks), the idea of drilling a hole through the head of a mainline rail has been met with some reluctance. Possible effects on rail fatigue due to the drilled hole have resulted in limited application of this option.

A significant advantage of the drilled-hole concept is that it can be used in embedded track because it produces little or no spillage or waste. Attachment 1 includes a full report

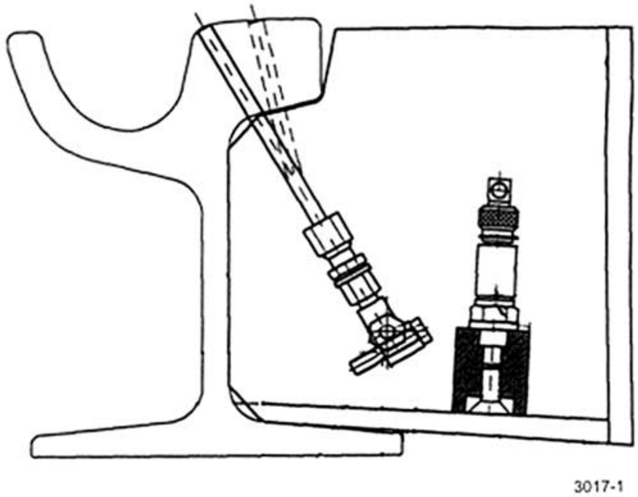

Figure 3. Drilled-hole application concept.

on a demonstration of the drilled-hole concept in reducing noise and friction.

The application shown in Figure 3 is limited to one hole on each rail at the site of application. The application is intended to provide a material to protect one or two curves. Thus, the amount applied and distance covered are limited.

2.3 ONBOARD LUBRICATION

Onboard equipment is the second most common means of applying lubrication on transit track. Installations using onboard equipment generally do not supplement lubrication with wayside units. The rare exception is a location with tight (i.e., low radius) curves, such as is typically found in yard leads. The decision to use onboard lubrication must be completely accepted by the mechanical department, which will be tasked to maintain the system. This method is often implemented to control wheel wear rather than to address noise or rail wear issues because accrued costs and benefits are credited to the mechanical department.

Freight railroad onboard flange lubricators and TOR systems use generically similar applicators. However, the application rate of material is generally much higher in freight railroad applications than in transit applications. Transit applications fit onboard systems to virtually every vehicle of the fleet. Usually one truck of each car, or one truck of each articulated set, is equipped with application systems.

Wayside lubricators must be spaced at intervals throughout the system, generally at or near curves, whereas the onboard systems apply small but consistent amounts of material at all locations along the track. This difference makes the onboard option ideal for a system with uniform route severity because all locations will receive approximately the same amount of material. While some systems increase output rate on curves, the amount is not variable by curve severity. Wayside systems can be concentrated in more severe curvatures or in site-specific, sensitive areas where noise control is a significant issue.

Most transit operators have not experienced favorable performance with onboard applicators as initially supplied by a vendor. Operators reporting the most success with onboard applicators have also been required to re-engineer the system for their own particular vehicle truck design. Also, onboard applicators generally operate with only one or two types of vehicle or truck design, thus limiting the number of variations and custom applicator designs required to ensure proper operation.

An improperly operating, broken, or defective applicator in a wayside system is characterized by a lack of grease or material being pumped. The result is one or two nearby curves exhibiting excessive wear and/or noise. The use of onboard applicators requires a different inspection and feedback approach. If the entire fleet becomes misaligned or is not properly applying lubricant, then a large number of curves on the system will exhibit noise and wear. The other, more common occurrence is that a single vehicle is applying lubricant improperly, is out of adjustment, or is out of material. The operator (or public complaints) can sometimes identify this condition. However, the small amount of residual, built up material on the rail will often protect one or more non-equipped or non-operating vehicles that follow.

Identifying an improperly operating vehicle is difficult. Most transit systems rely on frequent inspection to determine if maintenance is needed. Performing a rigid inspection of the application system while the vehicle is in the shop for routine work is essential. This helps to ensure that most of the fleet is applying the desired level of lubrication and/or friction control material and reduces the need for frequent line inspection to determine overall system lubrication effectiveness.

CHAPTER 3

FRICTION CONTROL MATERIALS

Materials for controlling friction are categorized as either lubricants or friction modifiers.

Lubricants decrease the friction levels, while friction modifiers can increase or decrease friction and will maintain a predetermined friction level based on design characteristics. Figure 4 shows the friction control characteristics of lubricants and a generic friction modifier.

A friction modifier is a material designed to change and control the coefficient of friction and behavior at the wheel/rail interface when applied to the TOR or wheel tread. This material is available in a form that allows it to be delivered to the TOR in much the same way as a TOR lubricant system delivers grease to the TOR. A grease lubricant will usually provide low friction levels, which may have disadvantages in terms of braking and traction. Although some operators have used lubricants in TOR applications, any excessive application can lead to traction control problems.

Friction modifier characteristics can reduce stick-slip and the resulting squeal while maintaining enough positive friction for normal braking and traction operations. Typically, target friction levels of 0.3 to 0.35 μ on top of the rail will provide a reduction in noise yet will not interfere with train handling. Excessive amounts of friction control material, however (as shown on the right side of Figure 4), can produce less-than-desirable friction levels and may allow wheel slip.

A number of demonstrations to evaluate TOR systems in freight railroad applications have shown that effectiveness from wayside-based systems can be observed at least 2 miles from the applicator. Freight applications generally pump larger amounts of material than is used in the transit environment. At one transit application, reduced noise has been observed at least 4,400 feet from a wayside TOR applicator. Effectiveness on freight railroad applications is determined by observing reduced curving loads and does not necessarily signify significant noise reduction. A field demonstration would be required to accurately validate a distance/noise reduction capability of TOR friction control materials. Because weather, humidity, rain, and other environmental issues can affect results, such a demonstration should be conducted with subway or open track issues in mind. In addition, a longer-term monitoring of the influence that TOR friction control has on corrugation development would be beneficial. Although this monitoring has been documented in one vendor's report about the vendor's material, the material is proprietary.

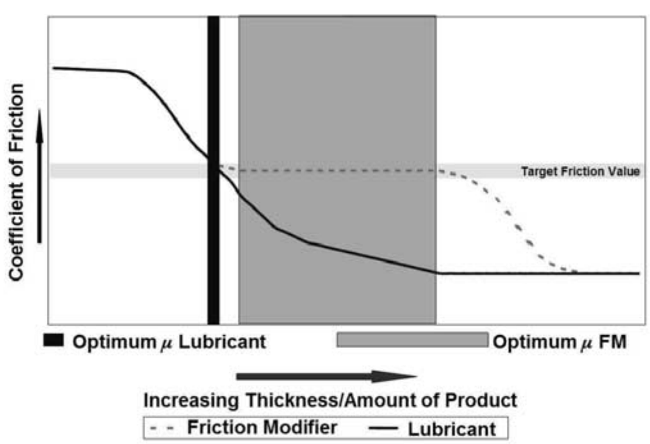

Figure 4. Friction modifier (FM) and lubricant performance.

CHAPTER 4

WAYSIDE TOR LUBRICATION/FRICTION CONTROL IMPLEMENTATION ISSUES

Rail lubrication technology was originally configured for gage face application to address freight railroad concerns of reducing rail and wheel wear, controlling truck steering forces, and reducing train energy. It was found that this technology could also address some rail/wheel interface–generated noise issues in the transit industry. However, when operated incorrectly, the lubricators tended to distribute excess lubricant onto the ballast and underbody of passing cars, causing undesirable operating conditions. Because some transit operators found that the conventional lubricators did not work satisfactorily from both environmental and safety standpoints, new technology evolved as manufacturers developed materials to meet the transit operators' needs. New concepts such as TOR lubrication have been found to be more effective in reducing noise and vibrations than gage face systems are.

While conventional gage face lubricators continued to use grease as their main source of friction control, material innovations such as friction modifiers have more effectively controlled noise. Since the potential value of friction modifiers was realized, at least one supplier of rail lubrication equipment has developed methods of applying friction control materials using a modified wayside applicator.

4.1 GENERAL ISSUES

Rail lubrication systems are in common use by the freight railroad industry, and many of the designs have been modified and/or developed for transit use. As part of this project, transit operators were interviewed to summarize their experiences with wayside and newer TOR application systems. The wayside systems currently in use are electrically controlled and allow adjustment over a wide range of conditions. Common positive responses concerning the modified wayside systems are as follows:

- The system was easy and quick to maintain.
- The system did not waste lubricant.
- There was success with inexpensive lubricant.

Some concerns raised by the transit operators of wayside systems are as follows:

- With electric wheel counter systems, wheels were miscounted because of electrical inference from power supplies.
- With accelerometer-based systems, wheels were miscounted because of nearby vibrations.
- The low end of the output duration is difficult to adjust.
- Occasional grease spillage resulted in a mess on the track and the surrounding area.
- Corrosion found on the applicator system was caused by friction control material carrier. (Newer formulations have resolved this issue.)
- Clogged applicator bars and friction control material evaporation caused delivery system clogging.
- Rain easily washed away friction control material.
- A unique rail/wheel profile at selected sites inhibited the proper transfer of material.
- The gage face and TOR systems required two different materials.

Specific issues for many of these general concerns are discussed below.

4.2 WHEEL MISCOUNT ISSUES

4.2.1 Magnetic Sensors

Most electric lubricators use magnetic- or vibration-based wheel counters to activate the pump systems. Activation is adjustable by axle count and duration. The pump is activated for a specific adjustable time after a specified number of axles have passed a site. For example, a setting of two axles and $\frac{1}{4}$ second would indicate the system pumps for $\frac{1}{4}$ of a second every two axle passes. Because of lubricant viscosity and startup delays, the amount of material delivered is not directly linear with adjustment increments.

In electrified territories, some operators have reported excessive wheel counts when compared with a known number of cars passing a site. The short-term solution has been to reduce output rate by specifying that the system activates after more axles have passed. Although this solution solves the immediate concern, it does not fix the problem.

4.2.2 Vibration Sensors

Some concepts use vibration sensors to activate the system. One transit operator has experienced false (i.e., unwanted) activation due to nearby passing trucks, buses, and trains that set off the system. Adjusting the sensitivity of the system to ignore signals under a certain level has solved this problem. However, reducing sensitivity may increase the risk of missing some axle passes.

4.3 OUTPUT DURATION ISSUES

In some instances, the lowest available setting for operating time duration is still longer than desired. Since these application systems have been developed for freight railroads, it may be beneficial to consider a shorter time of application for transit. With current designs, increasing the wheel count between pump activations can reduce the amount of lubricant applied. Although this method reduces the total amount applied, the result is too much lubricant applied per cycle. By providing shorter times in which the pump is active, one can reduce the overall amount of lubricant per wheel.

4.4 GREASE SPILLAGE ISSUES

Grease or friction control material spillage is an issue with both freight and transit operators. The spillage of greases and thicker materials applied by wayside applicators is a special problem with transit systems because of public visibility, close contact with other environment issues such as drainage into storm sewers, and difficulty for access to perform cleaning. The use of vehicle-based systems using liquid materials raises the issue of underframe and truck contamination from overspray and material fling-off from wheels. Some systems, such as those using a drilled-hole concept, apply such small quantities of lubricant that spillage and localized mess have not been an issue.

4.5 CORROSION

One operator reported that the friction control material produced significant corrosion to the applicator system, most likely by the carrier material. During a field inspection, evidence of corrosion was observed in the form of blistered paint and white material deposits around fittings. A revised material and an alterative paint were suggested as a solution by the vendor and have subsequently shown improved performance.

4.6 CLOGGING ISSUES

Some operators suspected that delivery system clogging was a result of the rapid evaporation of carrier materials. Such clogging is not limited to instances of friction control materials, as delivery ports using conventional and premium lubricants also were reported to be clogged. In some areas, the use of train sand has increased the tendency for clogging. Visual inspection followed by disassembly and cleaning of appropriate components has been the only viable solution.

4.7 RAIN

Rain and other environmental influences can affect the durability of materials. Experience has been mixed, with some transit operators reporting that rain had washed away friction control materials, while other operators reported it did not. In the cases where such problems were reported, the system recovers within 1 to 3 days. During the recovery period, some vehicles produced excessive noise.

4.8 MATERIAL TRANSFER ISSUES

Certain locations, especially after activities such as rail grinding or after trains with machined wheels, do not receive sufficient material to maintain desired friction levels. Spot, manual application of friction control materials is often required until the system wheel/rail profiles have returned to a conformal shape.

4.9 VARIATION IN MATERIAL PERFORMANCE REQUIREMENTS

Lubricating the gage face and controlling friction on the TOR requires a material to perform in two different ways. To date, no single material has been shown to be optimal for performing both functions. Two different materials—and therefore two separate reservoirs and application systems—are needed. In some cases, materials can intermix, and the most common result seen is braking or train handling issues (i.e., wheel slip).

CHAPTER 5

RESULTS OF DISCUSSIONS WITH OPERATORS

The recent innovation of using wayside applicators to pump specialized friction control materials has been implemented by several transit operator sites in Canada and the United States. The majority of operators trying prototype applicators have had success with this concept. Operators cite the concept as being the solution to their problems and solving the majority of their noise issues. Available data support these opinions. Still, most operators found this solution to be more costly than lubrication systems. Feedback from transit operators using wayside or onboard systems is summarized below. Detailed operator comments are provided in Chapter 6.

Operator A:

- The wayside-based friction control system is the solution to noise issues.
- The operator has confidence in the material and the delivery system.
- Squeal noise was significantly reduced from an excess of 100 decibels.
- Resident complaints decreased at both sites.

Operator B:

- The material works well under ideal conditions.
- Rain/wet weather washes away material.
- The system clogs in hot weather until the pressure overcomes the restriction.

Operator C:

- The system is very effective for TOR noise issues.
- There was a noise reduction at both sites.

Operator D:

- The material virtually eliminates noise in 100-foot-radius curve.
- Only manual application was installed; the full system was not yet installed.

Operator E:

- Turnkey installation and setup were implemented.
- The noise issue was addressed to the operator's full satisfaction.
- There were some slide and slip issues in wet weather on a 2- to 3-percent grade.
- The system was not in use because of safety concerns.

Operator F:

- The material performed well, but required high and somewhat wasteful application rates.
- The system did not work on an unusual rail profile with usual material dosage.

Operator G:

- High-frequency noise was reduced through the use of vehicle-mounted stick material that was applied to tread.
- Some additional low-frequency noise was due to applicator bracket vibration.
- There were no wheel flange wear issues due to onboard flange stick lubrication.
- Effectiveness was virtually eliminated when rain washed the product from the rail. Effectiveness was reestablished during normal operations when the product gradually built up a reserve film from the passage of trains.

Operator H:

- Flange wear was satisfactorily controlled by stick lubricators.
- The applicator brackets, as received, were unsatisfactory and required custom redesign.
- Experience with early tread friction control was unsatisfactory and resulted in wheel slip.

Operator I:

- An in-house design of onboard stick applicator bracket replaced an ineffective vendor design.
- Flange lubricator sticks provided adequate wear reduction to wheels.
- No wash-off from rain was experienced.

CHAPTER 6

GENERAL ISSUES DISCUSSED BY OPERATORS INTERVIEWED: WAYSIDE AND ONBOARD SYSTEMS

Vendors identified a number of transit operators having TOR lubricator/friction controls installed to address noise issues. Half of these transit operators had more than one system installed.

Interviews with operators using wayside systems are discussed in Sections 6.1 to 6.6. Interviews with operators using onboard systems are discussed in Sections 6.7 to 6.9. Attachment 1 includes a summary of responses from all transit operators interviewed. The most relevant responses have been summarized in Sections 6.1 to 6.9. These sections do not necessarily correlate with the numbered sequence in Attachment 1.

6.1 OPERATOR A

Operator A has been facing major wheel/rail-generated noise issues since the opening of the agency's light rail system in the 1980s. This noise was predominant in two locations. Site 1, located in a downtown area, consists of two curves connected by a short tangent section. Both curves are on a 2-percent grade with an 82-foot radius. Site 2 has a 300-foot-radius curve leading into a 600-foot-radius curve on an 8-percent grade. Light rail vehicles generate rail/wheel noise in excess of 100 decibels when negotiating through these curves, which are near a multistory apartment building. There had been a considerable number of resident complaints lodged about the noise. Early attempts to decrease and/or eliminate the noise with wayside (a.k.a. "trackside") grease lubricators, noise blankets or walls, and water were unsuccessful. Since the implementation of friction controls and a suitable delivery system, Operator A has been able to reduce and control noise levels for up to 3,500 feet from the trackside applicator. Squeal noise has stopped completely, and resident complaints have subsided.

Vehicle performance in regard to wheel wear and braking were reported as normal; however, there were some reports from vehicle operators of wheel-slip on an 8-percent grade. These occurrences were only after passing the trackside applicator. The wayside lubricator system was relocated to address this issue, and no vehicle operator has since reported wheel slip. The location of the wheel sensor should be carefully considered because the system configuration is susceptible to electrical power surges, which can cause the wheel counter to miscount. The recommended placement is on the non-return rail for systems with such a configuration.

6.2 OPERATOR B

A single system is installed in embedded track, and the trackside unit is installed on the platform ramp structure. The wiping bars and hoses are embedded and protected in steel boxes, and the wheel sensor is embedded directly into the roadway. Noise issues were the main concern, but the transit operator also reported excessive flange and restraining rail wear. The problem area addressed is a 250-foot-long, 82-foot-radius curve.

A wheel miscount from the magnetic wheel sensor during heavy current draw was an issue that surfaced early in the monitoring period. The heavy current draw caused the system to "see" more wheels than were actually there and thus to dispense more friction control material, resulting in increased material usage and waste. Adjusting the system by temporarily lowering the number of wheels needed to trigger the pump solved the problem. However, the manufacturer is exploring modifications to address the miscounting issue. The system works well under ideal conditions, but during extremely hot weather, the wiping bars tend to clog. This tendency is a result of high temperatures found in the railhead that cause the friction control material to dry at the wiping bar exit ports. Maintenance is higher during this period because crews are assigned extra duties to unclog the wiping bars. Another concern is that the material will wash away during periods of rain and snow runoff. After the track dries, there is an initial reapplication period before an effective amount of friction control material can begin to distribute along the track again. No vehicle performance problems, signal interference, or mechanical or electrical problems have been reported.

6.3 OPERATOR C

Noise is an issue in tight curves at two stations on this transit operator's light rail system. The turnaround at Site 1 has a 185-foot-radius curve that runs through a station platform. Site 2 has a 210-foot-radius curve at the end of a major station. A water spray system was used in previous, unsuccessful attempts to control noise. A friction control system has been installed at each site. The installations required running a longer hose than normal from the pump to the wiping bars.

Otherwise, no operating issues have been experienced. The operator has found the system to be effective for specific TOR rail/wheel-generated noise issues. There are no problems to report, and the system does the job as assigned.

6.4 OPERATOR D

Complaints of wheel squealing prompted this operator to explore noise reduction measures on a 290-foot-radius curve with a 2- to 3-percent grade. Initial tests that successfully employed a hand-applied, friction-modifying material prompted the purchase of two systems. No vehicle performance issues were detected at that time. A system was installed at each tangent prior to the curve, and the noise was managed and reduced. Baseline noise levels in the 100- to 115-decibel range were reduced to 82 to 87 decibels with the friction control material. Vehicle operators have since indicated that they have detected some wheel slide and slip, resulting in the system being taken out of service for safety reasons. An evaluation of braking/traction issues was to be performed.

6.5 OPERATOR E

Residents in a nearby apartment building have had a history of complaining about wheel/rail-generated noise. Earlier experience with gage face trackside applicators in which lubrication material was not spread satisfactorily prompted the operator to explore alternatives using friction control materials applied to the top of rail. To ensure that applying material to the TOR would not impact safety of operations, the transit operator and vendor successfully executed vehicle performance tests that consisted of braking trials with friction control materials. After showing that operations would not be impacted, two TOR application systems were installed in late 2000, with activation planned for a later date. Currently, this agency is also testing a vehicle-based onboard application system. No results from these trials are available at this time.

6.6 OPERATOR F

Operator F has 10 miles of double track and uses a number of trackside lubrication/friction control applicators to address noise issues. The majority of the trackside systems, which come from two independent suppliers, are grease lubricators and have been in use several years. Operator F also employs a few recently acquired friction control units.

The lubricant systems use grease as their primary friction-reducer medium. The units are composed of nitrogen gas–driven and pump-driven systems. They deliver low-cost grease to the TOR via tie-mounted grease gun housing. Besides reducing wheel/rail-generated noise, the systems are reliable and inexpensive to operate. They require infrequent maintenance, and servicing the systems is easily accomplished as part of the bi-weekly inspections. The grease lubrication systems are comparatively less expensive than the friction control units, as is the grease used in them. However, wet weather affects vehicle performance, and vehicle operators have reported instances of wheel slip in these conditions. It is believed that the wheel slip is caused by grease migration to undesired locations. The tendency to produce conditions leading to slip was addressed by modifying the control box to apply lubricant less frequently. Although the operator was satisfied with the operation of the grease-based lubricators, the availability of new friction control materials resulted in the purchase of several friction control systems.

Two sites on either side of a station were equipped with friction control systems. Initially, noise reduction was not achieved until the applicator was adjusted to a high material dispersion rate. This high setting resulted in material waste, as well as material splashing on equipment and ballast. Changing the configuration to a different style of wiping bars and a higher viscosity in the friction control material reduced usage. Still, the setup was not optimal, and further investigation revealed an unusual rail profile as the most probable cause of the problem. Re-grinding the rail to a traditional profile appeared to alleviate the problem.

6.7 OPERATOR G

Transit Operator G is a light rail system using articulated three-truck vehicles. It uses onboard systems exclusively. Each vehicle is equipped with a solid stick tread and flange system on the center truck. Two different material formulations are used: a friction enhancer for the wheel tread and a friction reducing material for the flange. Figure 5 shows an underbody view of a truck equipped with tread and flange lubricators.

The onboard systems have been installed since the inception of system operations to combat noise and to address potential public complaints. Because no operations have been conducted without these onboard systems, no information on rail wear, wheel wear, or noise without their use is available. Since implementation, the only periods of noticeably increased noise are after heavy rains wash the friction control material off the rail. Generally, the noise is reduced to normal levels within 2 to 3 days of operation after such heavy rains.

Observations and field experience confirming that noise levels increase after rain, then diminish after several days of operation, suggest that a working level of material is transferred to and remains on the rail. Steady state operations benefit from new material applied by each passing train. Thus, one or two trains not equipped with or having non-functioning wheel tread lubricators would still benefit from residual friction control remaining on the rail.

The trains appear to generate two categories of noise: high pitched and low pitched (i.e., high frequency and low

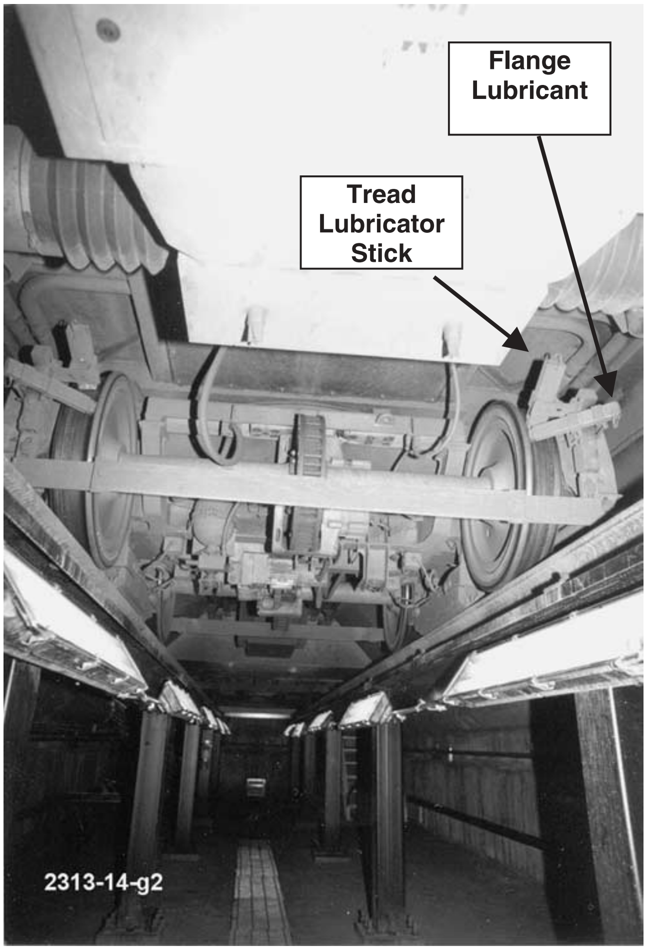

Figure 5. Underbody view of a truck equipped with flange and tread stick lubricators.

frequency). The common, higher-pitched squeal is significantly reduced or eliminated by the onboard stick system. The applicator apparatus, however, generates its own low-pitched noise. The relatively light material and support brackets tend to vibrate and produce lower-pitched noise levels, which are sometimes reported as equipment problems by passengers.

Recent changes in the physical shape of the stick material allow the top of a new replacement stick to fit into the back of the existing stick, thus interlocking old and new materials. This permits a seamless transfer from one stick to the other, allowing lubrication to be continually applied.

Lubricator alignment, stick configuration, and overall system adjustment are inspected on each car every 2 weeks. No dry cars are ever operated for extended periods of time. The entire fleet is equipped with lubricators (on one truck per car), and new cars are immediately equipped with lubricators when they are introduced. With the exception of dry rail after a rain, the entire system is kept at a steady state level of friction control. No issues with flange wear or rail gage face wear have been reported.

6.8 OPERATOR H

Transit Operator H is a heavy rail system (i.e., subway and above ground) operating two-truck equipment via third rail power. This operation uses onboard systems almost exclusively. Two axles of each vehicle are equipped with a solid stick flange system. Early in the investigation stage, this operator looked at tread application of a lubricant or friction control material, but this option was not pursued. Operating issues included difficulty with material buildup and subsequent wheel slide problems. Oil or liquid materials were investigated for onboard flange application. However, the potential of material migrating to the TOR and wheel tread also ruled out this option.

Solid stick devices successfully reduced wheel wear, but the applicator system provided by the vendor was unreliable, and frequent failures were encountered. A custom applicator design, based on innovations from the operator's own forces, ultimately became the standard. All cars in the fleet are equipped with a flange stick system. One wayside lubricator is installed at a non-revenue section of track to protect a turnout. However, experience to date with this wayside unit has shown poor performance.

Adequate operation of the flange system is seen in the extended periods between wheel truings. Cars are inspected in detail every 45 days, and the supply of solid stick lubricant blocks is assessed. Rail grinding is used to control noise at sensitive locations.

6.9 OPERATOR I

Transit Operator I is a heavy rail system operating two-truck equipment via third rail power entirely above ground. This operation uses onboard systems exclusively. Two axles of each vehicle are equipped with a solid stick flange system. Previously, this operator investigated the use of a roller unit mounted on the truck to distribute oil to the wheel flange. However, this type of system proved to be unacceptable. Oil migration to the wheel tread was a key problem, and the use of tread brakes by this agency compounded the problem of tread contamination. In addition, oil would splash onto the car underframe, providing an electrically conductive path to the ground. This path became a safety issue.

Although solid lubricants have shown excellent performance, the application system, provided by the vendor, required design upgrades for adequate service. Through trial and error, this transit operator produced an in-house design of an applicator system that was custom-fitted to the operator's trucks. The design was a successful, low-maintenance system. Stress raisers in the original design led to cracking and early failure of the assemblies due to vibration and mounting location.

To date, observations of track, wheels, and car bodies have shown no migration, splattering, or flinging of the material. Further, there have been no reports of braking-related problems.

Performance of the stick-mounted system to date has been successful, as noted by reduced wheel wear. Thin flange-related wheel repairs have not been required since implementation of the solid stick flange lubrication systems. Only infrequent adjustment has been required, and the current stick material is fabricated such that the sticks interlock with each other. Adjustment of the system is required after wheels have been turned on the lathe, as the alignment between the truck frame and flange will vary with different wheel diameters. Typically, each car uses about two lubricator sticks per month. As the entire rail system becomes more lubricated, the usage rate declines somewhat. No wash-off or removal has been noted after heavy rain.

This operator is very satisfied with the solid stick approach, but emphasizes that the entire fleet must be equipped and inspected and that periodic adjustment of the equipment is required. Most importantly, a viable operating solution required a dedicated effort and significant time to develop the correct applicator brackets for the system.

CHAPTER 7

ONSITE INSPECTIONS OF INNOVATIVE APPROACHES TO NOISE CONTROL

Three transit systems have recently implemented or demonstrated innovative methods and materials for friction control to mitigate noise and control wear:

- Portland Tri-County Metropolitan Transportation District of Oregon (TriMet), which has introduced the drilled-hole method of application.
- New Jersey Transit Hudson-Bergen Line, which introduced a combination of gage face lubrication and TOR friction control.
- New Jersey Transit Newark Subway, which demonstrated a prototype onboard system to apply friction control materials to the TOR.

Systems were inspected, and in-depth interviews and discussions were conducted, with field personnel in charge of lubrication system operation and maintenance.

7.1 PORTLAND TRIMET

Portland TriMet operates an extensive system of articulated light rail cars over a wide variety of trackage and alignment. Several years ago, a solid stick, onboard system was evaluated and had little success. Wayside-based gage face lubrication systems have been installed to control local noise and wear issues on standard T-rail (i.e., open track) at about 90 percent of the needed locations on the system. The wayside units have not found favor with the mechanical department because excess lubricant tends to get sprayed into the air or flung off of wheels, sticking to the underbody of passing rail cars. One underbody car fire has been traced to this excess buildup. Magnetic sensors activate the wayside systems, but these sensors have been prone to miscounts due to stray ground return currents. This problem has been resolved by adjusting the system to a lower activation rate than what might be required to compensate for the extra wheel counts from stray currents.

At one yard location, a water spray system was used in an effort to reduce the noise of cars turning on tight-radius curves near a residential neighborhood.

In recent years, TCRP funded a demonstration of plasma arc-bonded film on an entry/exit curve at the Gresham Yard. Results of this test reported in *TCRP Report 71*[1] suggested that reducing TOR friction to about 0.35 μ resulted in a significant reduction in noise. Immediately after application, the effectiveness was high and noise reduction was significant. However, material that was bonded to the rail was expensive and time consuming to apply. In addition, this material was not durable and disappeared within 2 to 3 weeks. Results suggested that controlling TOR friction reduced train-generated noise; hence, the decision was made to evaluate other application methods and materials.

In an effort to reduce noise at selected locations, Portland TriMet engineering staff is evaluating an alternative method of applying lubricant to the railhead. A number of noise-sensitive sites exist where sharp curves are located in embedded trackwork. One solution examined was the use of specially protected field side wiper bars. This technique would require installation of a relatively large cavity in the track at a congested part of downtown Portland and other selected areas. TriMet maintenance personnel currently apply a vegetable-based lubricant using a back-mounted weed sprayer system at selected locations. Although effective, the material must be reapplied daily, and the amount and location on the rail is difficult to control. The resulting overspray and excess accumulates in the flangeway of embedded track, building up a dirt reservoir.

An alternative application system was evaluated. TriMet engineers elected to install two prototype wayside systems featuring an electrically activated and driven pump delivering grease through a hole drilled in the rail. These are versions of units currently in track on the Edmonton, Alberta, system. The TriMet applications are modified to use an electric-powered pump rather than compressed nitrogen gas. Otherwise, layout and design are similar between the two operating properties. Figure 6 shows a cross-section diagram of the installation in a typical embedded track application. Figure 7 shows the actual installation.

The demonstration site on TriMet uses two application systems located in embedded trackwork on 100-foot-radius curves. Each system is intended to supply lubricant to reduce

[1] David Davis et al., *TCRP Report 71: Track-Related Research, Volume 1—A Compendium of Three Reports,* Transportation Research Board, Washington, D.C., 2001.

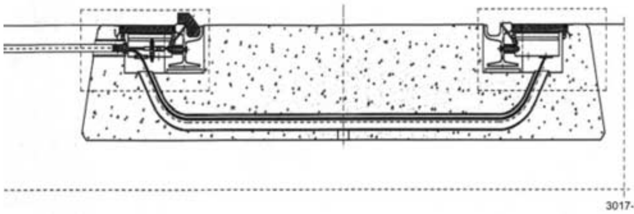

Figure 6. Cross section of a drilled-hole applicator in embedded trackwork.

noise only for one curve. Figure 8 shows an overall view of one curve and the applicator system. Figure 9 shows the applicator system enclosure. The system is activated by a vibration sensor mounted on the floor of a metal housing that allows access to the lines feeding the rail. The vibration signal is sent to the control box mounted on a nearby pole. The control box is supplied with 120 VAC from a commercial power source.

Vibrations trigger a sensor (located in the enclosure mounted in the street) that sends signals to the applicator system, which then activates the pump motor for a brief period of time. An interior view of the applicator system is shown in Figure 10. The pump is activated after a vibration threshold is exceeded. The duration of pump operation is also adjustable. The threshold vibration and pump duration require some field monitoring to set appropriate levels. At this site, vibrations generated by nearby bus operations and an adjacent railroad mainline under a bridge required fine-tuning of the threshold limit to prevent unwanted pump activation.

This site was selected by TriMet for installing and demonstrating the first drilled-hole concept because an ongoing construction project was already in progress. This project included

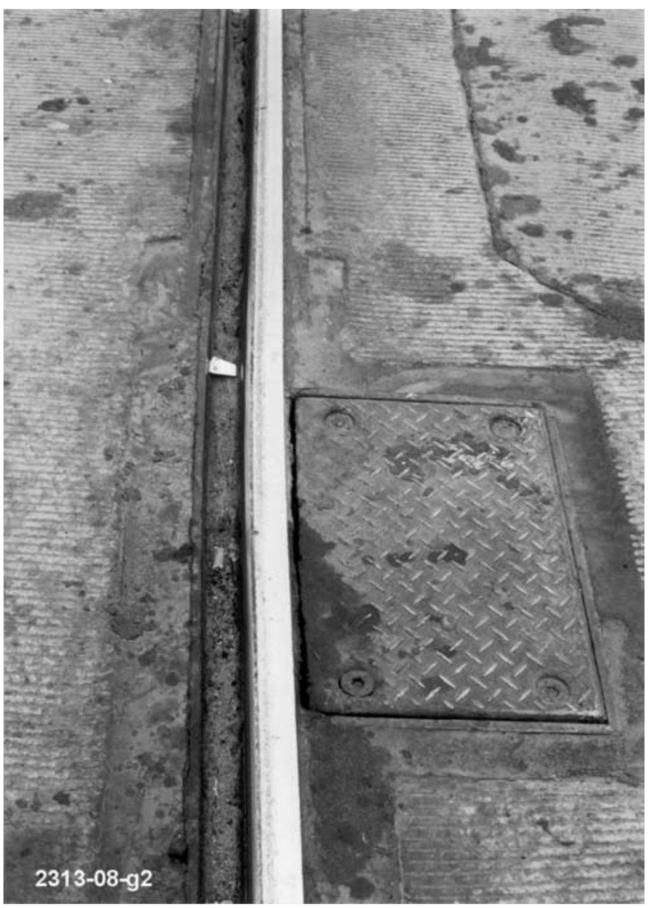

Figure 7. Street view of a drilled-hole applicator port.

Figure 8. Curve protected by drilled-hole applicator system.

Figure 9. Applicator system enclosure.

Figure 10. Interior view of the applicator system, showing grease reservoir.

installation of turnouts that would provide access for a new line extension in progress. During the turnout construction stage, a large (4-inch-diameter) conduit was installed to allow sensor cables and delivery lines between the applicator unit and the rail, thereby avoiding removal and reinstallation of pavement. A small metal cavity and cover were installed on each side of the rail to provide a housing and access for the delivery components.

As shown in Figure 11, the pump delivers 00 grade Teflon-based grease to each rail at the beginning of a curve via a single hole (about $^{3}/_{16}$ inch in diameter) drilled through the railhead. Grease is delivered to the head area by hoses, then goes into a fitting that is configured to the hole at the bottom of the railhead. Figure 12 shows the grease delivered to the rail after manual operation of the system. Delivery lines to each rail are configured to be the same length (from pump to drilled hole), thus producing the same backpressure to each rail. This helps to ensure that the rails receive a uniform amount of grease.

The grease reservoir is a clear plastic container allowing easy inspection of lubricant level (see Figure 10). Although refilling can be accomplished in the field, the preferred method

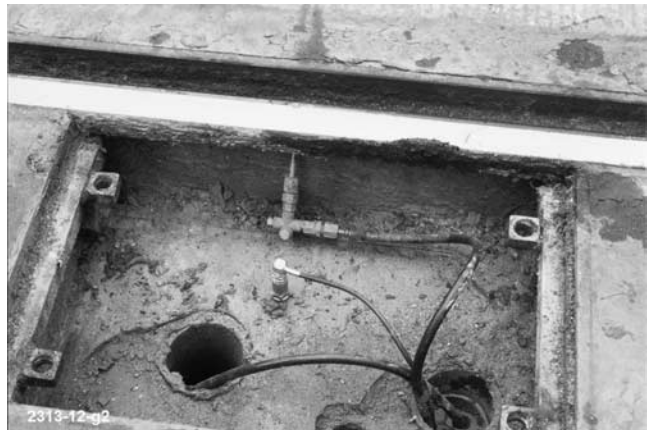

Figure 11. Drilled hole and grease delivery lines, with access hatch removed.

is to replace the reservoir with a full reservoir and refill the original reservoir in the shop. At the current consumption rate, with daily light rail car traffic exceeding 100 two-car trains, the reservoir (approximately 1 gallon) will last several months before refilling is required.

TriMet's experience to date with the drilled-hole concept has been positive, with only minor adjustments required to application rates during the initial setup phase. Frequent inspection of the hole has shown no metal flow developing over the orifice thus far. Noise reduction at the site is adequate, based on reports from car operators, bystanders, and onsite inspections. An evaluation of effectiveness using four different materials was conducted to document the noise reduction capabilities of this concept. TriMet installed a number of such application systems on a new line extension in 2004. This project is discussed in Attachment 1.

Figure 12. Grease flow after manual operation of the application system.

7.2 NEW JERSEY TRANSIT HUDSON-BERGEN LINE

Inspection and discussions with track personnel of the New Jersey Transit (NJT) Hudson-Bergen (HB) light rail line revealed that a wide range of innovative measures have been implemented to combat noise and rail/wheel wear. NJT operates three-truck, articulated light rail vehicles over a variety of track and routes, including open track through industrial areas and embedded track through older, established neighborhoods. This operation is relatively new. Noise and premature rail and wheel wear are major concerns.

Conventional wayside lubrication systems using two different types of lubricant have been installed to mitigate running rail gage face wear and guardrail wear. The lubricants include a biodegradable synthetic material that has a white appearance and a soybean-based biodegradable material with a dark appearance. Each material is being evaluated at locations where performance can be monitored.

General observation and comments on these lubricants suggest that the synthetic material is significantly more expensive than conventional greases, but much cleaner and easier to handle. Pumpability in all weather conditions is less of a factor. The soybean material, in the version currently being used, suffers from occasional cavitating problems and is difficult to pump at temperatures below 60°F. The soybean material is available in summer and winter grades to alleviate this problem. However, large temperature swings can be experienced over short time periods during spring and fall seasons, which makes the selection of the proper lubricant/friction modifier grade difficult. Both materials are being considered because of their environmental benefits.

Additional wayside-based application systems are in place at NJT using field-mounted applicator bars delivering a friction control material to mitigate noise.

At most locations of sharp curves, restraining rails are used to reduce or eliminate outside rail flanging and gage face wear. The restraining rails exhibit high rates of wear, as evidenced by frequent re-shimming of spacers against rail braces to maintain the necessary $1\frac{7}{8}$- to $2\frac{1}{16}$-inch clearance. If guardrail wear increases this distance, the flanges of wheels on the opposite side will contact the rail gage face and will cause noise and wear. As shown in Figure 13, both the restraining rail and gage face of the outside rail receive lubrication at some locations.

Guardrail applicator bars are usually located at the beginning of the curve and are configured to apply a small bead of lubricant to the back side of passing wheels. When an application system is properly operating, a uniform amount of lubricant is delivered to each port, allowing even transfer to passing wheels. (Refer to Figure 14.) Frequently, however, one or more ports are clogged because of contamination, resulting in non-uniform lubricant delivery. Figure 15 shows the result of two clogged ports. Note that the unclogged ports have excessive grease. This type of localized clogging causes the same amount of grease to be pumped out of the remaining ports, with the result of excessive grease being deposited at the fewer remaining open ports. In many cases, a single, large grease ball will be picked up by a passing wheel and either is flung onto the car body or falls to the ballast rather than being carried and deposited along the rail.

Figure 13. Location receiving both gage face and restraining rail lubrication.

The applicator hold-down bolts often stand too high and are sheared off by low-hanging components of passing railcar trucks. This is a special concern on trucks that have recently trued wheels because the wheel truing process reduces wheel diameter and resulting clearance. An alternative method of applicator mounting is needed in order to eliminate such damage.

HB track engineering staff has implemented a method of providing lubrication to both tracks from one lubricator pump, thus saving considerable cost at each location where feasible

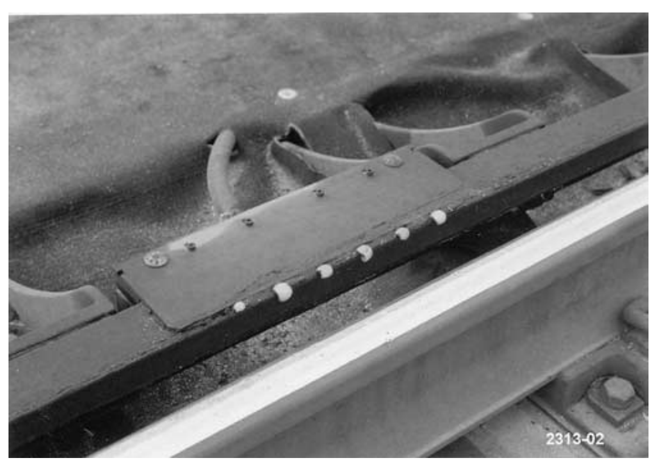

Figure 14. Lubricant pattern developed on restraining rail from dispensing unit with no clogged or blocked ports.

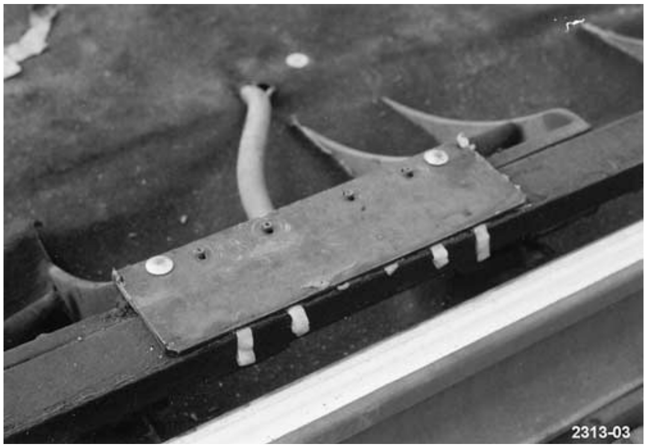

Figure 15. Grease pattern displayed by a dispensing unit with two clogged ports.

(see Figure 16). Traditionally, one sensor and one pump are located on each track. However, since this light rail line runs directionally balanced traffic, an alternative method was feasible. At almost all locations along this mainline, the number of northbound vehicles will match the number of southbound vehicles, and during most operations the time between vehicles passing either direction is very short.

The HB approach places one lubricator pump mechanism (tank/reservoir and pump) midway between both ends of a curve and feeds the applicator bars by long hoses (up to 100 feet long) in each direction. The system is activated by one sensor that is installed on only one of the two tracks. For example, a sensor installed on the northbound track will activate the system for a prescribed interval only after every northbound train. Southbound trains will not activate the system. The grease is applied to both the north and southbound applicator bars. After a northbound train has passed, a southbound train usually passes the site before the next northbound train. In such cases, the lubricant application cycle will be sufficient for both directions.

One location, with a longer distance between the applicator system and delivery bars, is equipped with a block heater to help keep the liquid flowing during cold weather. Sites where curves longer than about 250 feet (which require running lines longer than 125 feet) or where road crossings prohibit easy installation of delivery lines cannot use the HB approach. Observed performance and results from sites where the HB approach has been taken suggest that it is a viable option for reducing costs.

Noise reduction is the other major issue HB engineering staff has addressed. An aggressive program of installing wayside-based TOR application systems at key locations has successfully reduced noise. These TOR units use electrically controlled pumps and activators, delivering a friction control material through field-mounted applicator bars, as shown in Figure 17.

The applicator reservoir and pump system are virtually identical to those used in gage face and restraining rail applications. However, for TOR use the applicator bar design and friction control material are completely different.

The applicator bars have been heavily modified from gage face designs and deliver the friction control material to the field side of the rail, eliminating or severely limiting the amount that is applied to flange. The friction control material is designed to create a target friction level of approximately 0.3 μ once the carrier evaporates. The evaporation process is very rapid and has not resulted in any slipping or shunting problems to date. Observations of lubrication effectiveness during heavy rains suggest that the material is washed away. Immediately after a heavy rain,

Figure 16. Two mainline curve lubricator applicators supplied from one centrally located reservoir and pump system.

Figure 17. TOR applicator bars dispensing friction control material.

the noise levels increase, but they return to normal after several trains have passed.

Some clogging of delivery ports due to evaporation of the carrier has been reported, and, during early stages of the program, the material exhibited some settlement problems. Also, an element of the carrier appeared to attack the paint and cause corrosion of internal pump parts, as shown in Figure 18. The material formulation has been changed, and these problems have not recurred. Many of the application sites are in locations where frequent braking and acceleration occur, such as near road crossings and stations. Some train operators have reported wheel slip problems when applying maximum traction or braking. Sanding is automatic under such conditions. Inspection of these sites reveals significant buildup of sand, often mixing with excess material and depositing a thick, heavy paste in flangeways.

Carry distance from the applicator has been very acceptable, with effectiveness demonstrated by reduced noise at least 4,400 feet from the application site. Noise reduction is still effective even after the material traveled some distance, including through several reverse curves and long tangents of embedded track that is also exposed to vehicular traffic.

The TOR and gage face/restraining rail application systems are used at a number of locations along the system, but never directly adjacent to each other on the same track. One location (Figure 19) is equipped with a restraining rail lubrication system using a soybean material for southbound traffic, while on the adjacent track a TOR system applying friction control material is used for protecting northbound traffic. Each system has its own reservoir and applicator system.

Although the two reservoirs are within 25 feet of each other, no problems of refilling with incorrect material or incorrectly adjusting the lubricators have occurred.

Figure 18. Corrosion of tank components caused by friction control material carrier.

Figure 19. Site with soybean-based lubrication applied for gage face and restraining rail wear protection (right track) and friction control material applied to the top of the running rail (left track).

7.3 NEW JERSEY TRANSIT NEWARK SUBWAY

NJT has been investigating application systems and materials to obtain TOR friction control for reducing noise and wear. Applying friction modifiers to the top of the rail by use of a car-mounted application system offers some site-specific advantages over wayside/fixed systems and is being considered for a future extension that will use street and/or paved track. The street trackage will be located in a downtown area where contamination from wayside applicators is of specific concern. Previous evaluations by NJT using a friction modifier applied by hand (i.e., roller) indicated no adverse effect on braking distances.

NJT has been evaluating a modified onboard flange lubrication system to apply friction modifier to combat noise and vibration. It has been suggested that this application system can be configured to apply material to the top of the rail as well as back of the wheel, thus further reducing noise and vibration on street trackage without the need for wayside applicators.

A preliminary screening test to ensure that the material could be applied safely was conducted. This limited evaluation was considered preliminary to document changes in rail friction, braking distance, and wheel slip control reaction to the supplied friction control material. Results of this demonstration show that, when the material was properly applied, no adverse braking or wheel slip conditions were created. However, when excessive material was purposely applied, friction fell below 0.20 μ and caused wheel slip during braking and acceleration.

Results of this screening demonstration were not intended to encompass all issues and are not sufficient for sanctioning the full implementation of this material. The testing was conducted on a slow-speed (15-mph) yard section. The testing did not evaluate curved track, nor did it include data to document noise reduction. Because of time and budget issues, observations were limited to measuring changes in rail friction and braking system operation. Results suggest that, with proper control of application, successful results can be obtained. Attachment 2 provides a full report of this demonstration.

7.4 RESULTS

Although the above three transit systems were each inspected and evaluated, the TCRP panel chose Portland TriMet and NJT Newark Subway for demonstrations and measurements. These two systems had the least amount of information available about the performance of their innovative methods, and the panel wanted to increase information about those systems.

CHAPTER 8

CONCLUSIONS

8.1 CONCLUSIONS OF SITE VISITS, INSPECTIONS, AND INTERVIEWS

The application technologies, lubricants, and friction control materials reviewed are used for a variety of purposes, including controlling wear, noise, energy, and curving forces. The transit environment is especially sensitive to noise issues, and each of the systems/materials offers specific advantages and disadvantages affecting noise abatement. To aid in the selection of an appropriate friction control solution, user selection guidelines appear in Section 8.2. These guidelines are intended to direct the most appropriate solution for a given situation. The TOR wayside friction control application system using field-mounted applicator bars has been selected by most operators because it appears to offer the most effective solution to manage wheel/rail-generated noise issues and can be targeted to relatively long (up to 1 mile long) but site-specific, sensitive areas. The drilled-hole option, applying very small amounts of lubricant, has shown success for very short, very site-specific noise control.

Although these friction control systems function well for controlling noise, the friction control material is relatively expensive when compared with grease. The use of wayside application systems can affect functions such as vehicle acceleration and braking, especially where the application system is located near sites where these activities occur. Improperly adjusted lubricators in or near embedded track in roadways shared with motor vehicles and pedestrians can be a safety hazard because of the slipping/sliding danger to the public and to automobiles when excessive material is dispensed.

One of the issues experienced by the transit operators polled in this study was wheel counter errors. The location of the wheel sensor is critical because several operators have had issues with their wheel counters. Investigation of the problem has revealed that a current surge can cause the wheel sensor to over-count wheels, which results in over-lubrication with the associated undesirable operating conditions. The quick, but less reliable solution is to reduce the friction control material volume to correct for the over-lubrication. A more reliable approach seems to be placing the wheel sensor on the non-return rail, thereby avoiding wheel sensor miscounts.

Several transit agencies have reported that vehicle (i.e., train) operators experience wheel slip/slide when a system is placed near areas of high-traction demand, typically in the vicinity of a grade or near stations where starting and stopping require maximum adhesion. The general consensus of these agencies is that this observation by vehicle operators is incorrect. This belief is supported by the lack of substantiating data from onboard recorders to indicate a wheel slip occurrence. Further, in one location, rail friction data (using a tribometer) indicated that no unusual railhead conditions were present. Tests performed with freight rail trackside lubricators at the Facility for Accelerated Service Testing, located at the FRA's TTCI (in Pueblo, Colorado), also support the view that vehicle operators perceive wheel slip/slide in the presence of trackside lubricators, when in reality the lubricator is disconnected and inoperable.

The use of onboard flange and/or tread systems to control friction has been successful at a limited number of agencies, but only with a complete buy-in by management and by operating and maintenance personnel. The onboard option has been especially suited to transit systems with a small number of, and a limited variety of, vehicles. However, only one such system uses the option for noise control. Flange lubrication using onboard applicators has been a common solution to control wheel wear. Several operators who have investigated onboard systems dispensing liquid lubricants were dissatisfied with the amount of waste and fling of material and either dropped the option of onboard delivery or opted for solid stick materials. Off-the-shelf solid stick applicator units, as offered by vendors, have exhibited limited reliability. The most successful implementation of onboard systems has been with custom designed application devices, hardened for a particular truck or car design.

Regardless of the friction control solution selected (onboard or wayside), inspection, adjustment, and repair of the application system are an integral part of implementation. When used to control rail wear, periodic inspection of curves is essential to ensure that adequate lubrication is being applied. For noise control, feedback from vehicle operators is a first line of defense in detecting improperly operating application systems. This feedback is essential in eliminating potential public criticism.

8.2 SELECTION GUIDELINES

While this report covers a wide range of inspections and reports of current applications, vendors are constantly improving and developing existing products in response to feedback from users. New concepts and products are being offered on a continual basis, making any blanket recommendation difficult. This understanding is especially important when considering new technologies based on previous and sometimes poor experiences. Most vendors have incorporated comments and suggestions from unsuccessful demonstrations to improve products and application systems. In most cases, several generations of improvements have been integrated into the current generation.

Finally, every transit system has inherent unique characteristics that must be considered when selecting a method for friction control. For an existing system, site inspections of problem areas will often suggest special solutions or identify application systems that need to be modified. For new systems, problem areas can often be identified in advance and, when possible, be addressed (at least partially) by changes before construction. Occasionally, clearances and route alignment dictate a less than desirable layout. In such cases, an advance inspection is not possible until the line is built. However, using the same inspection techniques as those of a built line can be suggested.

Regardless of the solutions selected based on guidelines provided in this section, the overall friction management approach must also be reviewed by operating, track, and mechanical departments. This review will highlight areas of concern in advance and suggest where communication lines must be established. Key issues are summarized in Figures 20 through 23.

The general approach to selecting a friction control system is as follows.

1. Determine the concept (Figure 20):
   - TOR (use of friction modifiers),
   - Gage face (use of lubricants), or
   - Combination (including back of wheel issues).
2. Determine the application platform (Figure 21):
   - Onboard or
   - Wayside.
3. If the wayside platform is used, determine the application transfer mode (Figure 23):
   - Wiping bars or
   - Drilled holes.
4. If the onboard platform is used, determine the lubricant/friction modifier (Figure 22):
   - Liquid or
   - Solid.

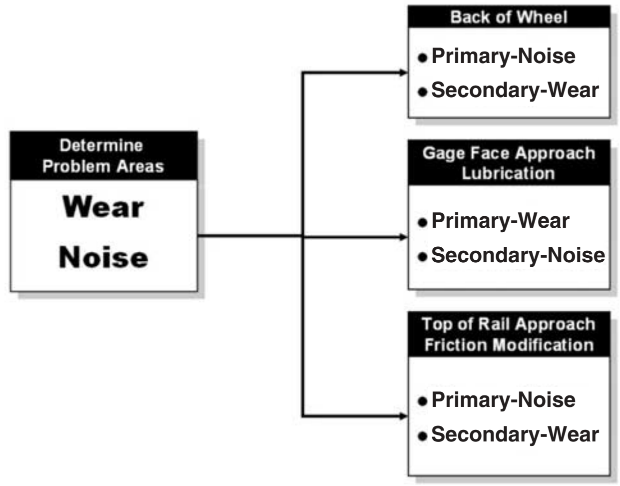

Figure 20. Problem area identification.

The following sections discuss this selection approach in more detail.

8.2.1 Concept

Issues most commonly addressed by friction control concepts are the following:

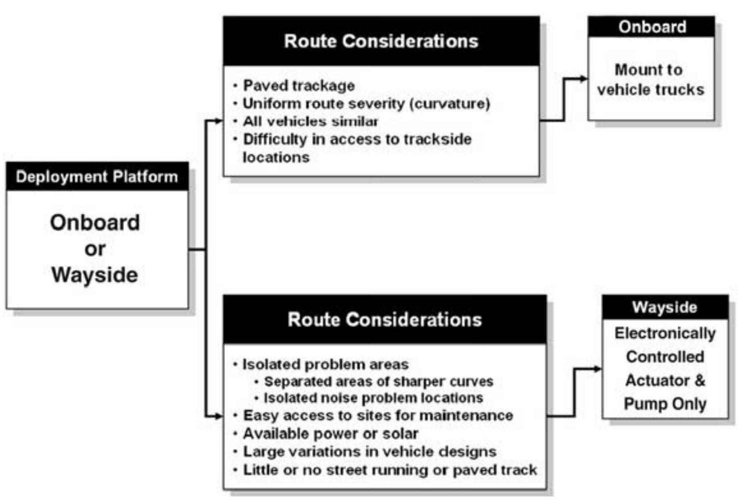

Figure 21. Onboard versus wayside applicators: route issues.

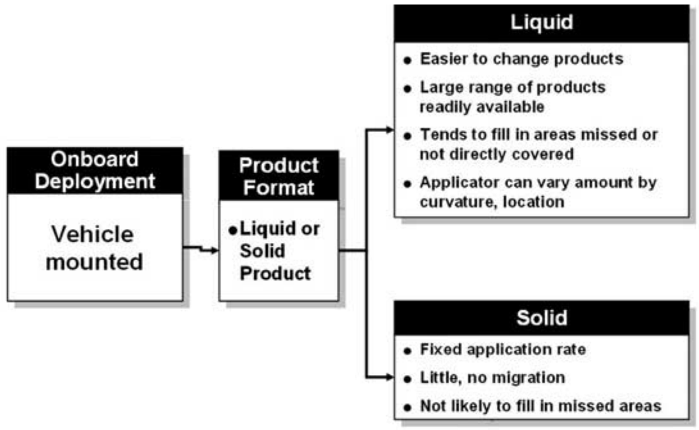

Figure 22. Onboard deployment: product format options.

- Noise—suggests TOR friction control.
- Rail gage/wheel flange wear—suggests lubrication of rail side/wheel flanges.
- Turnouts, restraining rails, and guard rails—suggest lubrication of wheel back on the back of rail or restraining rail.

Once the primary issue has been identified, the user can then determine the most appropriate application system concept for the specific transit property.

8.2.2 Application Platform

The issue of application platform is related to a transit system's layout, geometry, and equipment specifications. Wayside applicators are appropriate when at least one of the following conditions exist:

- Problem areas are isolated or well separated by longer tangent sections. For example:
  - There are a few sharp curvatures in well-separated locations.
  - There is easy access to sites for filling, maintenance, and adjustment of applicators.
  - There is either availability of power or access to sun exposure for solar panels.
- There is a large variation in vehicle types/truck designs. This situation makes onboard systems difficult to maintain because each vehicle type usually requires custom-mounted fittings.

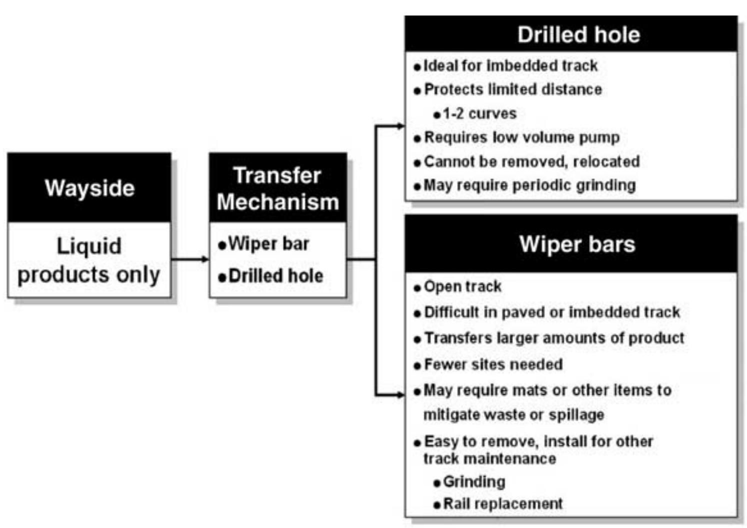

Figure 23. Wayside applicator issues.

If the wayside application is used, use electric or other non-contact methods for sensing trains and applying the product. (NOTE: North American experience to date with spray systems has not been successful in properly controlling product delivery. The use of a pump system is recommended for delivering material to fixed bars or holes.)

Onboard applicators are appropriate when at least one of the following conditions exist:

- Considerable street or paved trackage is encountered.
- Route severity (i.e., curvature) is relatively uniform throughout the system.
- Only one or two vehicle designs are in service.
- Access to trackside locations is difficult.

8.2.3 Application Transfer Mode

For wayside applicators, wiper bars are more appropriate than drilled holes when at least one of the following conditions exist:

- There is open track.
- A long distance (greater than 1 mile) of protection is required.

For wayside applicators, drilled holes are more appropriate than wiper bars when at least one of the following conditions exist:

- There is embedded/street track.
- Only one or two curves need protection.

8.2.4 Lubricant/Friction Modifier

Liquid can be applied by wayside or onboard applications and generally exhibits the following performance parameters:

- The liquid will move along the rail to fill areas where product is not directly applied.
- When the liquid is applied to the gage face, some migration to the TOR can be expected.

Solid lubricant/friction modifier should be considered only for onboard application systems and generally exhibits the following performance parameters:

- There is high variation in application under extreme temperatures.
- There is little or no migration (solid lubricant/friction modifier will not fill areas where it is not directly applied).

8.2.5 Other Issues and Application Methods

Other institutional and management issues to consider include the following:

- Track department issues: Provide inspection and feedback for non–wayside-based systems.
- Mechanical department issues: Provide primary maintenance and repair of onboard systems.

Other application methods to consider include the following:

- Hand application
  - In selected areas where wayside or onboard applications may not provide coverage.
  - On curved yard tracks with slow trains and back and forth moves.
  - On extremely sharp, isolated curves.
- Hi-rail or mobile-mounted systems

Lines with infrequent traffic or very slow speeds may require special attention in yards, in sidings, and in staging tracks.

ATTACHMENT 1:

Demonstration of the Drilled-Hole Applicator Concept for Applying Lubrication to the Rail/Wheel Interface*

* This attachment was prepared by Richard Reiff and Mike Sandoval from the Transportation Technology Center, Inc. (TTCI), and by Richard Smith from NSEW Engineering.

SUMMARY

Under sponsorship of the Transit Cooperative Research Program (TCRP), Transportation Technology Center, Inc. (TTCI), has conducted a survey of current and new practices for friction control used by the transit industry. Survey results indicated that transit organizations are evaluating new concepts in friction control, and top of rail (TOR) and alternative lubricant delivery systems/components lead the list of new and unique technologies.

The use of a drilled-hole applicator system to deliver small amounts of lubricant/friction modifier product was demonstrated on a segment of Portland TriMet trackage. Results suggest that such a delivery system provides measurable and significant wheel/rail noise reduction for distances at least 1,500 feet from the applicator. The rail friction produced during these demonstrations did not result in values considered to impact train operations, such as braking and acceleration. Four products were evaluated. Minor differences were noted between products in time/axle passes required to reach steady state performance. However, all performed adequately and eventually produced approximately the same rail friction levels and wheel/rail noise reduction. A finite element analysis of the drilled-hole applicator concept suggests that under typical transit wheel loads, no adverse fatigue or premature cracking is expected.

Additional evaluations under a wider range of curves and application rates are recommended. Further, product application duration and weather conditions should be evaluated.

1.0 INTRODUCTION

Under sponsorship of the TCRP, TTCI has conducted a survey of current and new practices for friction control used by the transit industry. Survey results indicated that transit organizations are evaluating new concepts in friction control, and TOR and alternative lubricant delivery systems/components lead the list of new and unique technologies.

While the survey identified many new initiatives in TOR friction control, performance of many of these have been monitored and reported by vendors and users. Some qualitative results are currently available for many of the newer lubrication and TOR friction control methods and concepts.

The drilled-hole applicator concept is one of the more recent innovations reviewed in this study that has been developed to control rail/wheel friction. This technology is lacking measured results from monitoring performance or effectiveness. For this reason, the TCRP project panel elected to fund a preliminary monitoring effort to document viability of this method of applying lubricants and friction control products.

While not an all-encompassing test, the intent of this demonstration was to document basic noise and friction control functions and benefits of applying lubricants though a hole drilled in the rail. The intent was to determine if this is a viable alternative application methodology that can be considered by other transit operators. This concept could provide an alternative means of applying lubricants/friction control products to the rail in addition to the more conventional applicator bars. The limited scope of this demonstration did not address all variations in lubricant carry distance or application amount or variations in weather, track curvature, rail/wheel profiles, and train braking. Because results show promising performance by this application method, additional evaluations may be warranted by individual transit operators to address specific concerns.

2.0 BACKGROUND

For years, railroad and transit operators have applied lubrication and, more recently, friction modifiers to the rail for controlling wheel and rail wear, energy, and noise. This has included the following lubricant application system configurations for both TOR and rail gage face friction control:

- Fixed/wayside,
- Mobile—train-based, and
- Mobile—hi-rail–based.

Recently, specialized applicator delivery bars and pumping systems have been developed to apply friction control products to the top of the rail. In the transit environment, the primary goal of such systems is intended to reduce wheel/rail noise and vibrations through exact metering and application of specialized lubricants and friction control products.

In most cases, freight railroads and transit operators use lubricant application systems that are very similar, and transit applications generally require smaller amounts of product to be applied in a more carefully controlled fashion. The control of excess product, visual indications of waste, and potential slipping hazards are concerns because transit applications are often in enclosed subways or subjected to foot and automobile traffic (such as in paved and embedded track applications). Such concerns led several transit organizations (including Edmonton, Alberta–Canada, and Portland, Oregon [TriMet]) to investigate alternative lubricant application configurations—specifically the drilled-hole concept.

The drilled-hole concept uses a single hole drilled into each of the right and left rails at a designated application site. Each hole, approximately $^{3}/_{16}$ inch (0.1875 inch) in diameter, is connected to an applicator/pump system and is intended to deliver a small amount of lubricant simultaneously to the top of both rails at prescribed intervals during the passage of a transit vehicle. (Refer to Section 4.0 for details.)

The drilled-hole concept is intended to apply sufficient lubricant only to cover one or two curves immediately beyond the applicator site. It is not intended to supply larger quantities of product normally associated with the conventional 24- to 48-inch lubricant applicator bars used with typical wayside lubricators or TOR systems.

3.0 OBJECTIVES

The objective of the demonstration was to document the overall reduction in wheel/rail noise and friction from lubricants/friction control products applied through one pair of drilled holes at the rail applicator site. Secondary objectives included assessing the difference in wheel/rail noise and friction reduction effectiveness at 200 feet and 1,100 feet from the applicator. Finally, performance differences, if any, of four different products were documented.

Because of limited time and budget, the demonstration did not include comparing the effectiveness of wheel/rail noise and friction reduction capabilities with conventional technology that uses lubricant applicator bars. In addition, only one site was available for this evaluation; thus, influence and variability due to track curvature, rail wear/profile, train speeds, train operation, and changes in weather could not be determined. Long-term durability of the hole with respect to wear or metal flow and the system applicator operation were not evaluated.

4.0 DRILLED-HOLE APPLICATOR CONCEPT DESCRIPTION

A feature of the drilled-hole concept is that it can be installed in the field using a portable drill, with little specialized equipment. For custom applications, the hole can be aligned to any specific location from the gage corner to the top of the rail. Figure 1 shows details of a single drilled-hole 0.1803-inch-diameter arrangement used by Portland TriMet. Figure 2 shows both rails equipped with drilled-hole applicators in embedded/paved track.

The exact location of the drilled hole for Portland TriMet applications is such that it distributes lubrication to the gage corner. This setup not only supplies grease to the gage face/

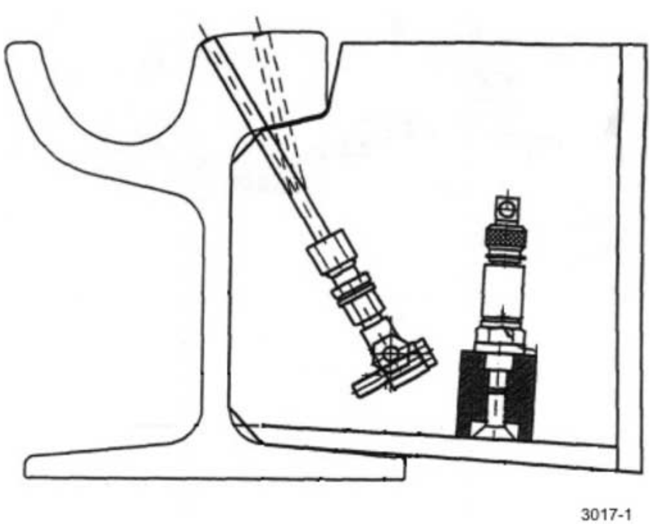

Figure 1. Drilled-hole concept—detail of one rail.

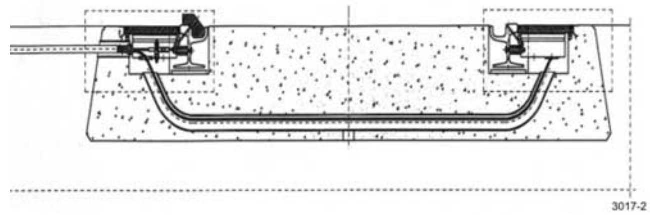

Figure 2. Drilled-hole concept—in embedded track showing both left and right rails.

wheel flange for wear control, but also allows some grease to migrate to the TOR, thus reducing noise. Specific applications for other systems could be configured to apply more grease to the gage face (by a lower hole) or to the top of the rail (by a hole nearer to the top of the rail). Because this location is on tangent track, little or no direct contact with passing wheels was observed. However, TOR applications would be susceptible to metal flow from passing wheels.

One drawback of the drilled hold application is that holes cannot be relocated or adjusted after installation. Thus if a site is experiencing incorrect application of lubricant on and along the rail, adjustment of applicator alignment is virtually impossible. Also, if the applicator location needs to be moved, or the rail is changed, a new or replacement hole must be drilled.

Further, the use of drilled holes for wayside application devices with lubricant such as the friction modifiers of the viscosity used in this demonstration requires the site to be located on track with no cross level (0.0 inch) in order to reduce product waste. The lubricant is pumped to the TOR area for pickup by the treads of passing wheels; thus, any superelevation can lead to product running off the rail and creating an unbalanced left or right rail friction condition.

Although the drilled-hole concept is not new to the freight railroad industry (where it has seen limited use in some yard track, often with use of a "dutchman" or filler rail to host the hole), the idea of drilling a hole into the rail head has usually been met with some reluctance. Concern over possible effects of accelerated rail fatigue due to the drilled hole has resulted in limited application of this option. A limited evaluation of the fatigue issues of a drilled hole in new 115-pound RE rail is included in Section 10.

The significant advantage of the drilled-hole concept is that it can be installed in embedded track with little visual indication to the public. This reduces the chances for vandalism and interference, yet still allows lubrication to be applied at specific noise-sensitive locations. Figure 3 shows a typical in-street installation, and Figure 4 shows the same location with the cover plate removed to show details.

Portland TriMet personnel selected the drilled-hole applicator concept for use on the new I-5 line extension. This decision was made after prototype demonstrations on embedded track near the Portland Convention Center and several down-

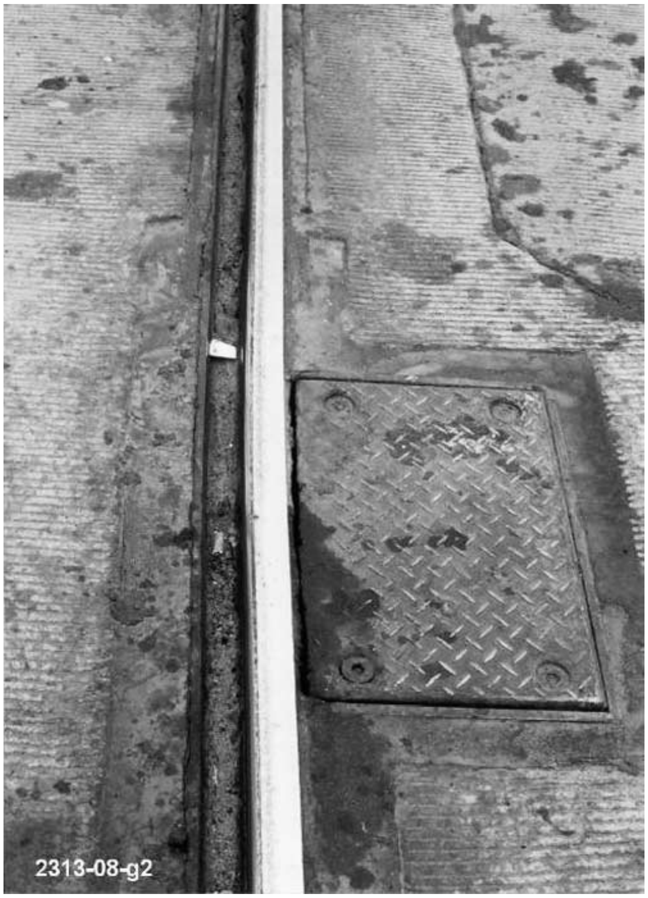

Figure 3. Typical in-street installation of a drilled-hole applicator.

town city curves and stations confirmed that drilled-hole application produced little or no spillage or waste, yet appeared to reduce wheel/rail noise. As with any lubricant application system, the controls and pump must be periodically inspected and adjusted to prescribed settings to ensure proper operations.

5.0 TEST SITE DESCRIPTION

The test site selected was on the penultimate curve at the north end of the new I-5 line extension, as is shown in Figure 5. The gray circle represents approximate data collection limits, the details within which are shown in Figure 6. The track had been in full revenue service for approximately 6 weeks, and several months of train operator training had taken place prior to conducting the test. The test site was on open track (i.e., not embedded), which allowed the use of an unmodified hand tribometer for collecting rail friction data. Other sites featuring embedded track along the I-5 line that were equipped with drilled-hole applicators were also examined and considered for this test; however, significant nearby noise from traffic would have impacted the gathering of wheel/rail sound data. Figures 6 and 7 show the placement of the microphones used to quantify wheel/rail noise at the test site. Shaded areas in Figure 6 show the limits of tribometer readings on curved track segments.

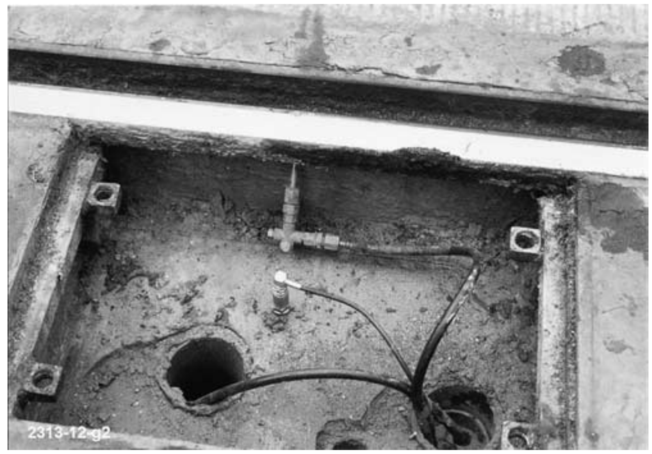

Figure 4. Cover plate removed to show applicator details.

Figure 8 presents typical time-based signatures for visual review. The top signature was measured while the rails were dry. The bottom is the measured wheel/rail noise generated when the track was fully lubricated.

Appendix A of this attachment provides additional details of the sound measuring and friction monitoring equipment used in this test.

6.0 DESCRIPTION OF DATA

Lubricant performance was monitored using two primary data collection devices, one for rail friction and the other for wheel/rail noise generated by passing trains. In addition, a test log consisting of train information, weather, and other system status comments was prepared.

6.1 Rail Friction Data

Rail friction was measured using a hand push tribometer. This device allows one location on the rail head (gage face to any spot on the TOR) to be measured. Friction values for which the tribometer is valid range from a low of 0.1 μ (well lubricated) to a high greater than 0.5 μ (dry). Values over 0.6 μ are beyond the normal calibration of the device and signify very dry rail.

Friction data are collected while pushing the tribometer along a 15- to 25-foot length of rail, during which time four to five readings are displayed. If the last three readings are within 0.03 μ of each other, the operator then averages these readings and records the value. The measuring wheel must be adjusted to collect data over the desired running band on the rail or location on the gage corner or face of the rail.

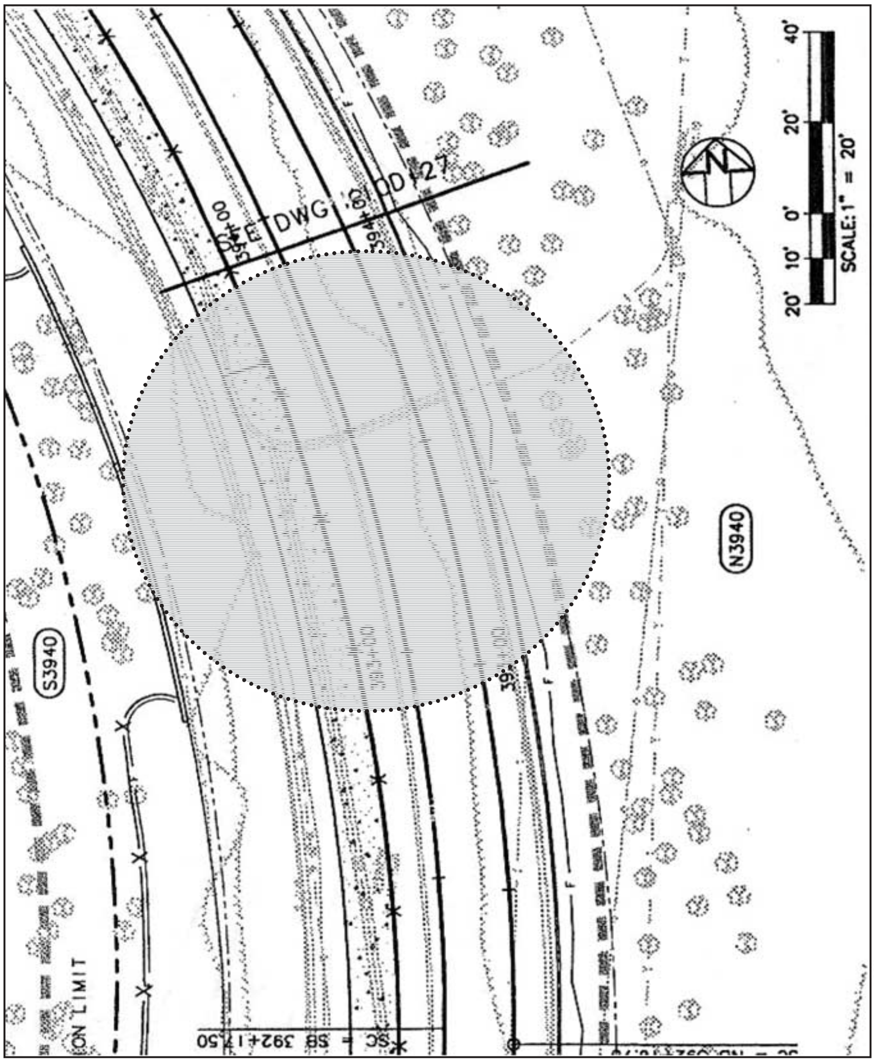

Figure 5. Location of noise and friction measurements.

Because of new rail in place at the test site, friction was measured near the top center of each rail and on the gage corner.

Appendix B provides a summary of all rail friction data plotted by axle pass after activation of the lubricator. Appendix C contains a tabular listing of measured friction values.

6.2 Sound/Noise Data

Sound data were collected from all passing trains using three separate microphones (refer to Figure 7). See Appendix A for a summary of these data. A reference sound level meter was placed at the center of the two tracks going north and south. Stereo microphones were placed on either side of the north and southbound tracks approximately 6 feet away from the outer rail of the transit tracks. The center reference microphone was approximately 4 feet from the inner rail of each track. The centrally located microphone was about 20 inches above the TOR, whereas the field microphones were about 15 inches above the TOR. Appendix A lists specifications for each microphone used during testing. Wires ran directly from the centrally located microphone to a data collection computer. The field side microphones contained their own independent digital storage for continuous sound recording and were turned on and off at the beginning and end of each test day.

The field side microphones collect continuous sound throughout the day. The digital acoustic information stored in the stereo field side microphone's flash memory was archived each evening. The total data storage from the two field side recording units was roughly 10 gigabytes.

The majority of the test data and the summary information used in this report are derived from the reference microphone placed between the two tracks at the test site. Corroborative acoustic information from the field side microphones is available as needed. A transit vehicle took roughly 5 to 10 seconds to pass the recording microphones. In most cases, a total of 30 to 40 seconds of data were recorded for each passing car unit, providing 10 or 15 seconds of extra recorded informa-

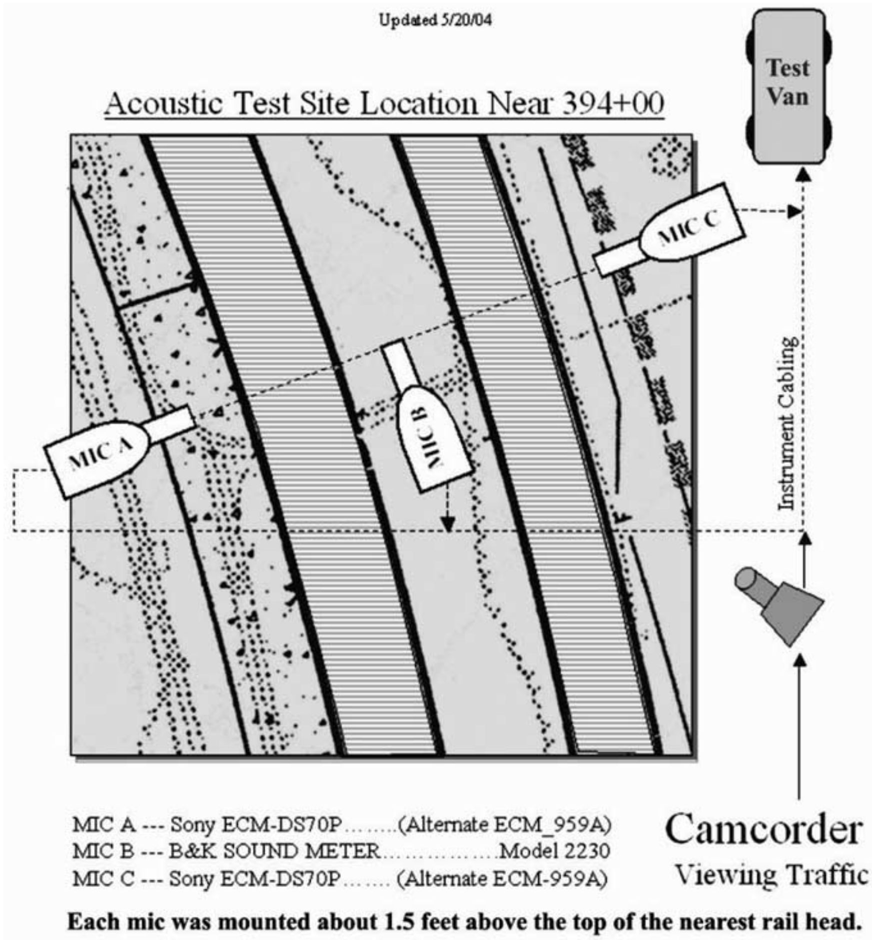

Figure 6. Test site showing location of microphones.

tion on either side of the passing vehicle. The unused portion of each recording, however, provided some insight on the background noise at the test site during various car passes.

Calibration of the reference microphone located between the north and southbound tracks consisted of placing a pistophone over the microphone barrel and recording its output voltage signal on the data collection computer. In addition, a "reference voltage signature," which was generated by the internal electronics of the sound level meter itself, was also recorded to hard disk. This method of calibration provides a total throughput check of the entire sound measurement system.

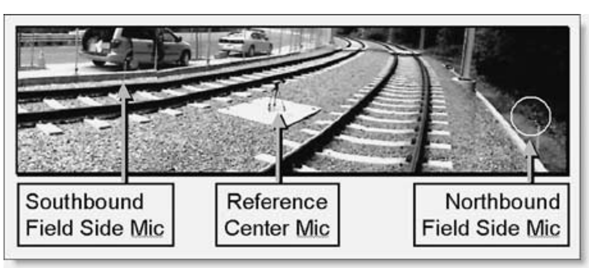

Figure 7. View of microphones used during study displaying relative locations.

6.3 Train Log

At least two observers were at the site during testing to monitor train operations and collect data. Thus, for every vehicle that passed, a visual observation was made and the vehicle number was recorded in a log. Train log data allowed post-test correlation between vehicle number and wheel/rail noise to be made.

Appendix C provides a summary of trains logged during this test.

6.4 Weather Conditions

The test site was subjected to occasional rain showers during lubrication tests and during the track dry-down periods. The dry-down periods took such a long time that they were almost always impacted by a rain storm; thus, this information is not included in the report. The nearest weather station

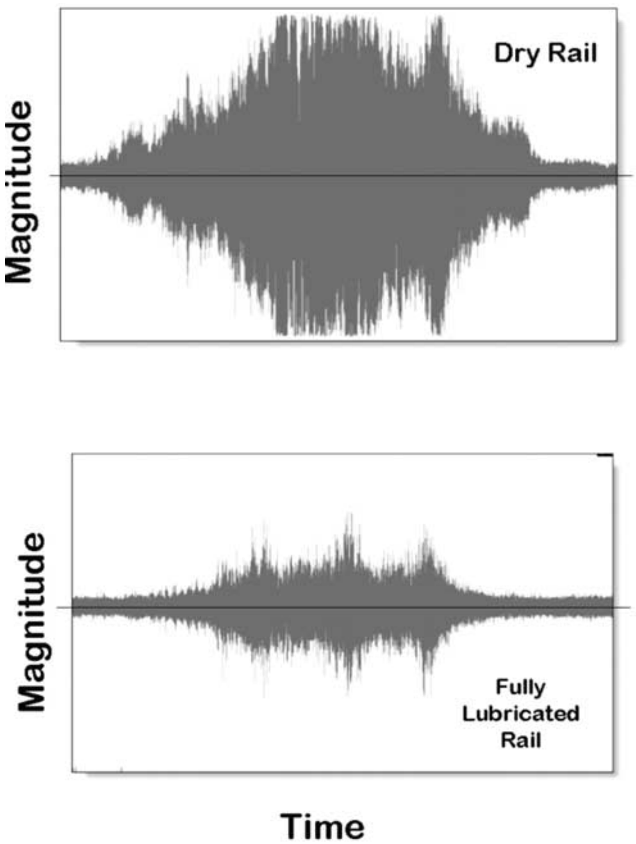

Figure 8. Typical time-based noise recordings taken on dry (top) and lubricated (bottom) rail.

at Portland Airport (approximately 7 miles to the east) was used for gathering information; however, localized rain storms were often experienced. Weather data are summarized in Appendix D.

The Portland area weather conditions varied during the test period. Temperatures remained between 55°F and 65°F the first 7 days of testing. There were heavy rains just prior to the start of test, which was the test period used to prepare the site for dry baseline conditions. During this time, lubricators were shut off so that the rail surfaces would be thoroughly dry before starting the test. The resulting rail condition produced a clean surface at the start of the test.

Hourly temperatures were obtained from the Portland airport, and the temperature archives are available via the Internet through the National Weather Bureau. This information was collected and is listed in Appendix C, along with the times of passing trains throughout the period of data collection.

Ambient temperatures during the test varied widely, typically from 55°F to over 90°F. Temperatures during the first 7 days of testing ranged from 55°F to 65°F. During the last 3 days of testing, the temperatures rose rapidly in the mornings from 60°F to 65°F. During the last day, the temperature went above 90°F. Data in Appendix C show the range of temperatures that occurred during each test day, as well as the hourly temperature swings that occurred.

6.5 Applicator Pump Records

Figure 9 shows details of the applicator control system. This applicator can be operated in three different modes: by vibrations, by number of lubricant applications per hour, or by pump motor control. The tests were operated in the vibration mode, and the parameters remained constant throughout the duration of the test. The unit also has a counter that tracks how many times the unit was activated. This feature was used to determine how many trains had passed while the test team was not present. Appendix C provides the system's adjustment (on/off) log.

7.0 TEST PROCEDURE

Data were collected using the passage of normal revenue service trains. No special operating instructions, speeds, or changes to train operations were involved during the 2-week test period. Most data were collected Monday through Friday between 6:45 a.m. and 6 p.m. This period included rush hour trains with full to nearly full loads and off-peak trains with few passengers.

Unfortunately, testing was interrupted several times because of rain, which washed off some of the lubricant tested and made determining durability (dry-down rates) problematic.

Each sequence of evaluations followed the same general procedures after the initial set of trials:

1. The two nearby existing lubricant applicators were turned off—one on the northbound track approximately 200 feet south of the measurement site and the other on the southbound track approximately 1,100 feet north of the measurement site.
2. After confirming dry rail conditions (TOR friction > 0.4 μ), the lubricant applicators were activated.
3. Sound and tribometer (i.e., friction) readings were collected every hour on both northbound and southbound tracks (approximately every four to five trains on each track).
4. Steady state was declared when the tribometer and quick-look noise data remained steady for at least 90 minutes (three similar readings [$\pm$0.05 μ] over the 90-minute period).
5. After steady state operations were documented, the lubricant applicators on both northbound and southbound service were deactivated.
6. Once both rails returned to a dry state (as monitored in Step 2), another product was tested.
7. Each product used the Portland TriMet applicator system.

The first product was evaluated after an extended dry-down (3 days) to determine worst-case dry rail performance.

INSIDE OF CABINET

Figure 9. Details of pump control system.

8.0 PRODUCTS EVALUATED

For purposes of this evaluation, four lubricants/friction modifier products were used. The baseline product currently used by Portland TriMet is Product S.

Prior to these evaluations, a number of lubricant and friction modifier producers were contacted for participating in this test. For vendors agreeing to participate, samples of each product were sent to Portland for preliminary screening evaluations. These samples were installed in existing wayside drilled-hole applicators on the same I-5 line and observed for several weeks. Provided they exhibited adequate pumping performance and indicated a reduction in wheel/rail noise, they were kept for detailed evaluations of wheel/rail noise and friction performance.

The four products all have proprietary formulations; thus, descriptions below are based on Material Safety Data Sheet (MSDS) information. Specific details of ingredients and additives are not shown.

- Test Product A: Soybean-Based A
  - Appearance and odor: Black grease with characteristic vegetable odor
- Test Product S: Synthetic Lubricant
  - Appearance and odor: Translucent white to slightly yellow, slight odor
- Test Product D: Biodegradable Lubricant
  - Appearance and odor: Tan grease, mild odor
- Test Product B: Soybean-Based B
  - Appearance and odor: Greasy material with black color, no odor

9.0 RESULTS

Detailed performance for each product evaluated is shown in the appropriate appendix. Examples of typical performance for several products are shown, along with a summary table for the complete matrix of products included in the appendix.

9.1 Rail Friction Results

Tribometer data for dry to lubricated periods are shown using axle counts before and after the lubricant applicator was activated. To allow easier comparison, the axle count at the time of activation is shown as zero; thus, friction data collected on dry rail before the applicator was activated are shown as a negative axle count. Plots for all products are included in Appendix B.

A typical time history plot based on axle counts is shown in Figures 10 and 11. For the examples shown here (from Appendix B), performance is for Product B. Figure 10 shows friction as measured on northbound trains where the lubricant applicator was approximately 200 feet from the measured site. For southbound trains, friction was measured about 1,200 feet from the applicator and is shown in Figure 11. In addition,

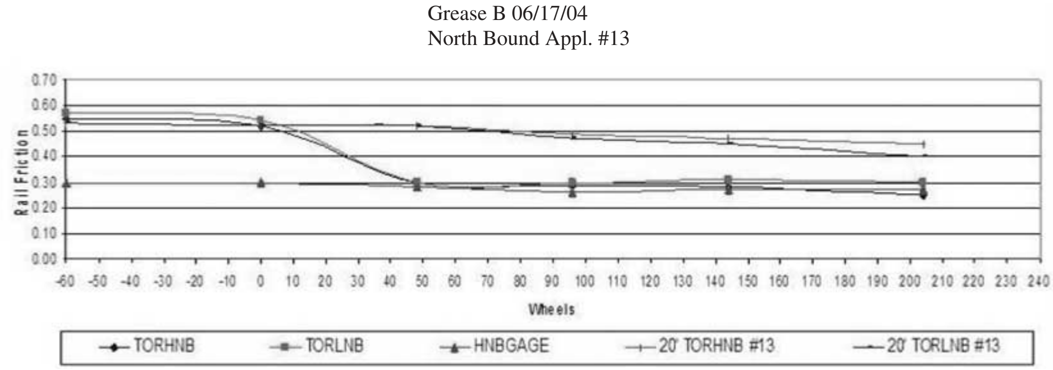

Figure 10. Time (axle) history of friction, lubricant B, northbound trains.

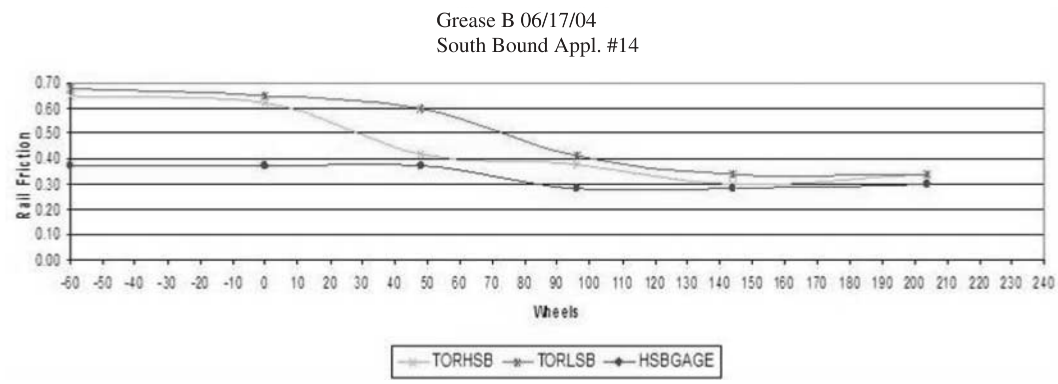

Figure 11. Time (axle) history of friction, lubricant B, southbound trains.

plots for northbound trains show friction at “20 TOR,” which is for the top of the rail about 20 feet before the applicator. These data were taken on the top of the rail before the applicator to indicate if any TOR contamination was present.

TOR friction shown in both figures suggests that rail conditions prior to the zero count were dry, while some gage face contamination remained. Although it was desirable to start each product from a dry rail condition, this was not always obtainable, and because of time limitations, after TOR conditions confirmed “dry,” the lubricant application cycle was activated.

As the starting condition for each product varied, it is not viable to show the drop or change in friction. Comparisons are made showing steady state friction and time (i.e., number of axles) required to reach steady state. These comparisons are summarized in Tables 1 (northbound) and 2 (southbound).

Examination of Tables 1 and 2 suggests that all products evaluated produce TOR friction in the targeted range of 0.3 µ to 0.4 µ on both rails. Data for 200- and 1,200-foot distances shown in the “Axles Passes to TOR Steady State” column indicate significant difference in left to right rail performance.

For northbound trains, all products produced the desired level for TOR friction within an average of 80 axle passes (about seven two-car trains), while several reached steady state in 50 axle passes, or about four two-car trains. The number of axles required to obtain steady state friction was about the same for gage face and TOR applications: each application had an 80-axle average and a range of 50 to 100 axle passes needed to reach that value.

Southbound trains took longer to reach steady state levels (on average taking 130 instead of 80 axle passes for TOR),

TABLE 1 Steady state friction performance—northbound trains (200-foot carry distance) group averages use both rails to determine value

Product	Steady State TOR Friction (µ)	Axle Passes to TOR Steady State	Steady State Gage Face Friction (µ)	Axle Passes to Gage Face Steady State
D	0.35	50-120	0.28	95
S	0.35	100	0.29	100
A	0.30	50-100	0.30	50
B	0.30	50	0.28	85
Group average	0.33	80	0.29	80

TABLE 2 Steady state friction performance—southbound trains (1,200-foot carry distance) group averages use both rails to determine value

Product	Steady State TOR Friction (μ)	Axle Passes to TOR Steady State	Steady State Gage Face Friction (μ)	Axle Passes to Gage Face Steady State
D	0.38	120-160	0.30	60
S	0.30	140*	0.30	100*
A	0.35	85	0.30	130
B	0.33	145	0.30	100
Group average	0.34	130	0.30	100

* Rain may have interfered with performance during this test run

which is logical because the distance from the applicator was 1,200 feet compared with 200 feet for northbound traffic. The steady state friction levels were only slightly less effective for southbound trains (a difference of 0.01 μ), which indicates that once products are applied they tend to reach the same steady value (over the two ranges of distance).

The primary objective of this application method is to reduce wheel/rail noise near the applicator; thus, performance of TOR friction is a secondary indicator. Table 3 shows the ranking in performance between products for near (northbound) and far (southbound).

9.2 Noise Data Summary

Appendix A provides the complete set of reduced noise data for each product. Figure 12 shows a sample summary set of typical noise data for two selected products (S and B). Single dots represent outliers while the solid band represents a larger number of occurrences

Data in Figure 12 show the wide range of noise for each car pass. Average values are needed to determine performance differences, if any. Table 4 summarizes noise data for all lubricants and both directions over all frequency bands. Note that the average decibel noise reduction for Product A is less than others because of a different starting condition. Initial noise levels for Product A on northbound runs were different than with other products. By comparing the average values of noise generated after the track is lubricated (right most column), the variation among products reveals little difference.

Table 4 lists the average decibel noise reduction (Column 3) calculated for each tested lubricant. Average noise signal levels for three major rail conditions—**Dry**, **Transition** in going from dry to lubed, and **Steady State Lubed**—are included in Columns 4, 5, and 6, respectively. Lubed rail is quieter than dry rail for all lubricants. All lubricants show approximately the same amount of noise reduction. The higher the positive values in Column 3, the greater the change in going from the dry to lubed condition. As noted before, the performance of Product A is different because it started with a "quieter" rail condition due to residual contamination remaining on the rail. The last column indicates very little difference (if any) in the four lubricants when the rail was fully lubricated.

The data shown in Figure 13 contain all frequency bands in the collected spectra taken under the operating conditions listed. If only frequencies in the 800- to 2,000-hertz range were averaged, the noise reduction would be less. However, if a frequency band from 5,000 to 20,000 hertz were averaged, then the noise reduction benefits would be as great as 20 decibels.

Figure 13 illustrates how noise is related to pitch (i.e., sound frequency) when rail is either dry or lubricated. This figure contains two separate average spectra from more than 100 distinct frequency bands. Each of the displayed spectra is the mathematical average of the acoustic noise from more than 400 car passes for each condition, dry and lubricated. The top spectrum of the figure is derived from all the dry rail-car passes, and the lower spectrum is from all the lubed rail car passes. The sound levels displayed indicate that the noise reduction obtained from adding lubricant to the rails is largest in the high-frequency range. The frequency span covered in the display is from 800 to 20,000 cycles per second. Most of the frequency range presented is detectable by humans.

The most important result of the acoustic evaluation is that the wheel/rail noise generated by transit vehicles is significantly and clearly reduced when lubrication is added to the rails. These particular tests provide evidence that noise reduction is highly correlated with sound pitch. Relative to noise emanating from dry rail, acoustic levels are reduced from 10 to 20 decibels when the rails are well lubricated. This is good news for both the general public and the transit authorities.

TABLE 3 Summary of axle passes required to reach TOR steady state

Product	Northbound Axles to Steady state TOR (μ)	Product	Southbound Axles to Steady State TOR (μ)
B	50	A	85
A	50-100 (75 average)	S	140
D	50-120 (85 average)	D	120-160 (140 average)
S	100	B	145

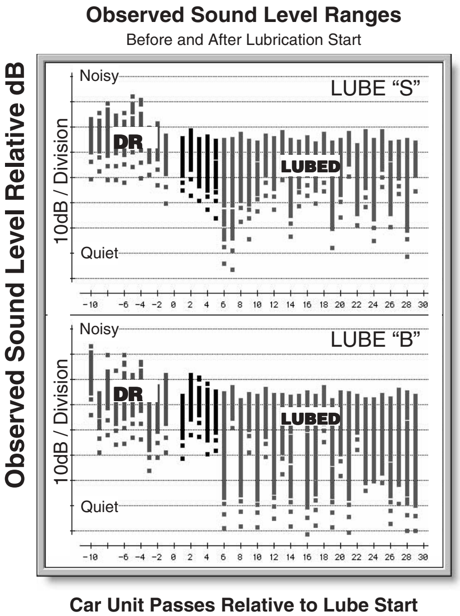

Figure 12. Noise summary for lubricants S and B, combined northbound and southbound performance.

The following conclusions can be drawn from the acoustic data gathered for this report:

- The placement of a bead of lubricating grease at a fixed point on a transit rail is one of the most important factors in effectively reducing wheel/rail noise beyond the point of lubrication.
- No single lubricant evaluated in this study was more effective than another in reducing wheel/rail noise. Each tested lubricant is an effective reducer of acoustic noise when the lubricant is present on the rail.
- The relative noise reduction attained by all the tested lubricants is in the range of 10 to 20 decibels. The amount of sound level reduction depends strongly upon the frequency (i.e., pitch) of the noise generated. The higher-frequency components of the generated noise are reduced the most.
- The passing of only 5 to 10 car units can significantly reduce wheel/rail noise generated beyond a lubricator application point.
- The acoustic benefits realized from applying a lubricant to the rail continues for several days (or 200 to 400 cars) after shutting down the lubricator. Weather conditions dominate the grease dry-down rate.

10.0 RAIL DEFECT/FATIGUE ISSUES WITH THE DRILLED-HOLE CONCEPT

The concept of drilling a hole in the rail head (especially at the running surface) has raised issues by many transit and railroad operators as creating a potential crack origination zone. To address this issue, TTCI conducted a finite element analysis (FEA) on an existing 115-pound RE section model of rail using a generic rail and wheel load.

The first case study used conditions that would be found on tangent track, using a wheel load of 20,000 pounds in the vertical direction and no lateral load. This case would simulate worst-case dynamic load conditions for a typical location of

TABLE 4 Summary of noise data, both directions, for all products evaluated

Test Lube Code	Vehicle Traffic Direction	Average Decibel Noise Reduction	Average noise signal level for dry rail (-10 to -1 car unit passes relative to lube start)	Average noise signal level for transition rail during the period from dry to lubed (1 to 6 car unit passes relative to lube start)	Average noise signal level for steady state lubed rail (7 to 29 car unit passes relative to lube start)
A	NB	9	-41	-46	-50
D	NB	16	-34	-43	-50
B	NB	15	-37	-44	-52
S	NB	14	-35	-46	-49
A	SB	8	-38	-46	-47
D	SB	6	-39	-39	-45
B	SB	6	-40	-42	-46
S	SB	8	-34	-44	-42

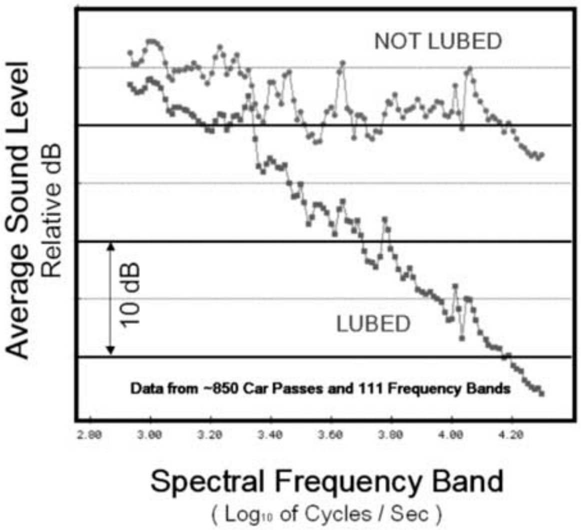

Figure 13. Average spectral sound level for conditions of dry and lubricated rail.

a drilled-hole applicator on tangent track with no lateral curving forces. Results with this scenario suggest that no adverse fatigue results should occur.

The second case study simulates the same vertical situation but with lateral curving forces of 14,000 pounds. Although these forces are much higher than most transit operations would likely see, this is a worst case condition that might be seen in spirals or if a track anomaly was nearby. In this case, the stress generated was much higher than before and metal flow or deformation would likely occur around the hole. Chamfering of the hole is recommended to reduce problems on areas subjected to lateral forces.

The Portland vehicles have a static wheel load of 13,000 pounds. The 14,000-pound lateral force used would occur only in a curve or under severe dynamic hunting conditions. Thus, results of this study for use in the transit environment are conservative. Other site variations, such as operation on curves or alternative profiles, may introduce higher contact stresses and should be evaluated on a case-by-case basis. Appendix E details this study.

Long-term wear or metal flow of the drilled hole at the rail surface was not measured or monitored. During the 2-week test period, no change in shape or size was noted. Also, other drilled-hole installations on Portland TriMet that have been in place for over 2 years have shown no significant degradation or metal flow. This suggests that little long-term maintenance will be required provided that the drilled hole is installed in a tangent section with no lateral loads.

11.0 DISCUSSION: SUMMARY/CONCLUSIONS

Given the variability in weather, measurement tolerance, and operating conditions, all products performed approximately the same in steady state friction and wheel/rail noise reduction. Some differences were observed between products in the number of passing axles it took to obtain a steady state value. These differences suggest that, for a curve directly adjacent to an applicator, steady state values for TOR friction and wheel/rail noise can be achieved after 50 to 120 axle passes. For a curve located 1,200 feet from the applicator, steady state can be reached after 85 to 160 axle passes.

The primary objective of the test was to document whether the drilled-hole applicator concept is viable. A variety of lubricants exhibited reductions in wheel/rail noise and friction control when applied though a single hole in the rail.

The limited scope of this test did not provide enough information to determine definitively which grease is optimum for the Portland operation because a number of performance issues could not be evaluated, including:

- Dry-down performance (i.e., durability),
- Rain wash-off resistance, and
- Train braking performance.

Dry-down performance is a measure of lubricant durability and would be measured by monitoring wheel/rail noise and friction after the application was ceased. Dry-down performance could not be properly monitored because of interference from rain and the length of time (more than 2 days) some products remained active. In addition, some products continued to flow from the applicator hole after the pump was deactivated, most likely due to gravity feed. To prevent this flow, it would have been necessary to disconnect the applicator nozzle from the rail for each test (and subsequently reconnect it), which was not practical. Dry-down performance is a key parameter if the applicator system becomes disabled, damaged, or runs out of product.

Resistance to wash-off from rain is a key issue, especially in a climate like that of the Portland area. If a product is easily washed off, then it must also rapidly be reapplied. Wash-off performance was not monitored during the limited time of the test.

Finally, train braking performance was not measured during the test. The test was situated near the end of the I-5 extension. Shortly after the northbound trains passed the site, they were required to brake for the Expo Station. Likewise, southbound trains departing the station immediately passed over the applicator and freshly applied lubricant. During the 2-week testing period, no reports of wheel slip/slide or traction problems were received from the train crews. A more rigorous and controlled test of braking is recommended to ensure that alternative products exhibiting rapid migration and carry do not interfere with train operations.

12.0 FUTURE RECOMMENDATIONS

The data suggest that a variety of products can produce desired friction and wheel/rail noise reduction. However, these products were evaluated under similar, dry weather conditions.

Additional evaluations are suggested to document performance under the following conditions:

- Test wash-off resistance to determine performance under rain,
- Evaluate stop distance and braking tests with materials on top of the rail,
- Mix with sand to determine performance at sites where train sanding occurs, and
- Evaluate under warmer and cooler ambient conditions.

While all products tested performed adequately under Portland TriMet operations, results show that some products might achieve steady state levels more quickly from a dry rail condition. Depending on wash-off performance of the products, this performance issue could be key, provided that other parameters such as train braking are not impacted.

13.0 ACKNOWLEDGMENTS

Field coordination and cooperative efforts from Portland TriMet were essential in conducting this evaluation. Significant time and effort were provided by Mr. Ken Kirse and Mr. Jack Hagel of Portland TriMet in pre-test evaluations as well as during the testing.

Test lubricants/friction control products were provided with the cooperation of Mr. Hans Van Lange of ALL_RAIL, and Dr. Lou Honary of the Ag-Based Research Program, University of Northern Iowa.

APPENDIX A

ACOUSTIC EVALUATION OF TRIMET RAIL LUBRICATION*

TRANSIT RAIL LUBRICATION SYSTEM BENEFITS

TYPES OF LUBRICATOR APPLICATION SYSTEMS

FIXED POINT—TOP OF RAIL SYSTEMS
MOBILE VEHICLE–BASED LUBRICATION SYSTEMS
MOBILE HIGH RAIL APPLICATIONS

SINGLE POINT—TOP OF RAIL LUBRICATOR FACTS

LUBRICATORS HELP CONTROL FRICTION AND WEAR
LUBRICATORS REDUCE ENERGY LOSS
LUBRICATORS REDUCE GENERATED TRANSIT WHEEL NOISE

FIXED POINT TOP OF RAIL APPLICATOR MAINTENANCE FACTS

APPROACH IS USEFUL FOR COATING SHORT RAIL DISTANCES OR SINGLE CURVES
METHOD GENERALLY REQUIRES SMALLER AMOUNTS OF LUBRICANT
SCHEME IS COMPATIBLE WITH FOOT AND AUTOMOBILE TRAFFIC
AMOUNT OF LUBRICANT CAN BE CAREFULLY CONTROLLED
MAY BE USED IN CLOSED SUBWAY SYSTEMS

TRANSIT SYSTEM WAYSIDE ACOUSTIC DETECTION FACTS

ACOUSTIC DETECTORS IMPOSE NO SERVICE DELAYS
INSPECTIONS TAKE ONLY A FEW SECONDS FOR ANY PASSING CAR
APPROACH IDENTIFIES OPERATING PROBLEMS WITHOUT SPECIAL INVOLVEMENT
“AS NEEDED MAINTENANCE” IS ACHIEVABLE WITH FEEDBACK INFORMATION
IT’S A MAINTENANCE PREVENTION TOOL WITH A “SOUND” FUTURE
SOMETIMES IT JUST PAYS TO LISTEN

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* This appendix was prepared by Richard Smith of NSEW Engineering.

This document contains the acoustic findings from a study with two related tasks, Both car noise and rail friction data were gathered from a transit line in Portland, Oregon. Approximately 850 cars passed the site during the study.

Figure 1—View of one of the study's transit car units heading north on the yellow line.

ACOUSTIC EVALUATION INTRODUCTION & SUMMARY

The main objective of the acoustic portion work is to measure the sound generated by the wheel-rail-interface both before and after applying four separate lubricants to the rail. The test is located between two rail lubricators separately installed on northbound and southbound tracks near the site. This site selection allows engineers to assess the reduction in generated noise as well as rail friction from separate lubricant applicators. Sound level generation caused by track curvature, train speed, rail wear condition, and train operation are inherent to the chosen test site.

The collection of acoustic and rail friction data was completed over a 2-week period. The location was near the extreme northern end of the newly opened yellow line of the transit system. The Portland Oregon TriMet authority engaged engineers from the Transportation Technology Center located in Pueblo, Colorado, as well as an acoustic consultant from North-South-East-West (NSEW) located in Clifton Park, New York, to handle the desired rail friction and noise gathering details.

The results from the test performed fall into categories, including

- Character of the noise changes created by adding lubricant to the rail head (as well as lubricant type),

Figure 2—Photo of test site near north end of transit line close to the Portland Expo Center. Note: Northbound rail is near photographer. Southbound rail is nearest autos in the photo.

- Frequency dependence and magnitude of the noise reduction,
- Effectiveness of lubricant's noise reducing character relative to the distance from application, and
- Temperature related sensitivities of the wheel/rail noise generated.

The most important result of the test research is that the noise generated by transit vehicles is significantly and clearly reduced when lubrication is added to the rails. Although this result may be well known by folks who work with rail lubricators, only a handful of engineers may know that these particular tests provide evidence that the noise reduction is highly correlated with sound pitch. Relative to noise emanating from dry rail, acoustic levels are reduced from 10 to 20 decibels when the rails are well lubricated. **This is good news for both the general public and the transit authorities.**

Figure 3 shows how noise is related to pitch (i.e., sound frequency) when rail is either dry or lubricated. This figure contains two separate average spectra with over 100 separate frequency bands. Each of the two displayed spectra is the mathematical average of the acoustic noise from approximately 400+ car passes. The top spectrum of the figure is derived from all the dry rail car passes, and the lower spectrum is from all the lubed rail car passes. It's clear from the sound levels displayed that the noise reduction obtained from adding lubricant to the rails is largest over the higher-frequency range. The frequency span covered in the display is from 800 to 20,000 cycles per second. Good ears are sensitive to most of the frequency range presented.

During the test, noise information was collected from transit vehicles that passed over two separate fixed point lubricators, one on a northbound track and another on a southbound track. The distance from the test recording microphones to the separate lubricators was approximately 200 and 1,200 feet. Further details are given in this report, but it is now understood that it takes a longer time for the wheel rail noise character to change (in both magnitude and frequency character) when a lubricator is located farther from the actual point of listening.

Although finding the temperature sensitivity of the noise levels generated by the wheel rail interface was not an objective of the test, the ambient temperature varied widely during the test. Again, a more in-depth presentation of the observed ambient temperatures will be made in this report, but a slight sensitivity of rail noise to temperature is established analytically.

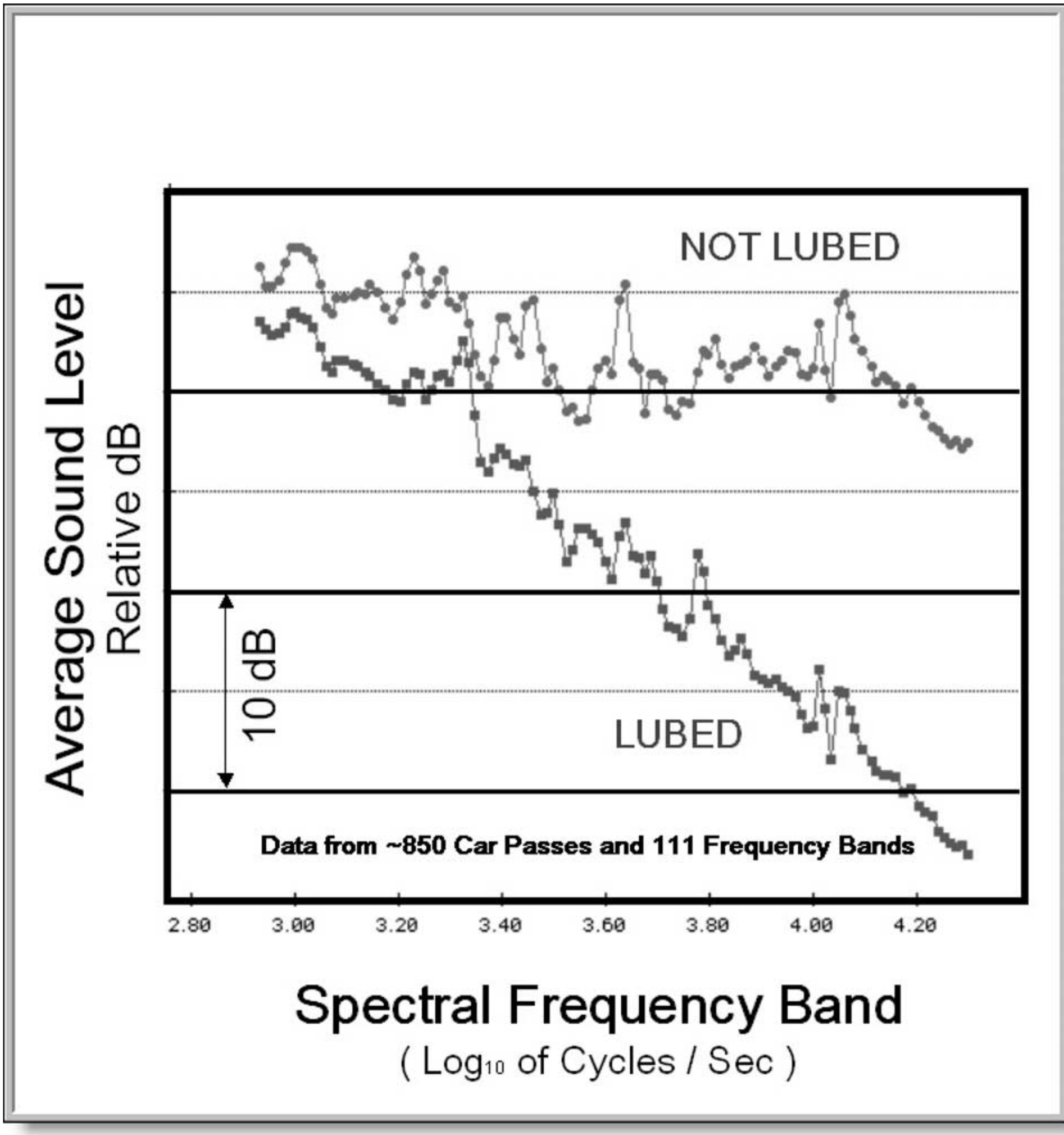


Figure 3—Image depicting average spectral sound levels for dry and lubricated rail.

Although large reductions in sound level were observed when going from dry to wet rail, there were also observable temperature sensitivities to sound generation under both conditions of lubrication. It appears that lubricated rail is less sensitive to temperature change than dry rail is. Dry rail appears to get quieter at a rate of about 3/10 decibel per degree Fahrenheit increase in temperature, whereas lubricated rail drops in noise output at much less than 1/10 of a decibel for every degree Fahrenheit increase in temperature. Since temperature could not be controlled during the test and four separate lubricants were applied throughout the duration of the study, these findings need additional experimental evidence to be fully confirmed.

One of the major desires of this effort was to determine if different types of lubricants provide varying amounts of effectiveness in noise reduction. Four separate lubricants were applied to the rails during the study:

1) Soybean-Based A . . . . .Coded in this report as A

2) Synthetic Lubricant . . . . .Coded in this report as S

3) Biodegradable Lubricant . . . . . .Coded in this report as AR

4) Soybean-Based B . . . . .Coded in this report as B

Four separate plots contained in Figures 4 and 5 represent some of the acoustic results obtained from the four lubricants used in the test. Data collected both before and after the four lubricants were applied are presented. Further discussion on this topic will be given in the main body in this report, but there are only minor variations between the noise reduction properties of each lubricant tested. All tested lubricants significantly reduce noise by similar amounts immediately (or very soon after) the test lubricants are applied. A noise reduction of nearly 20 decibels is realized after only five or ten car units have run by the fixed point top-of-rail (TOR) lubricator. See Figures 3, 4, and 5 for a summary of this finding. Since there were two separate distances to the north and southbound traffic data from Figures 3 and 4 are further separated by direction of car travel in Figures 21 and 22 in Annex D. Table 3 in Annex D contains a numeric summary tabulation of the acoustic responses shown in the figures by tested lubricant type as well as by direction of car travel.

Once any of these lubricants is applied to the rail, it takes a long time and many car passes to do away with the noise reducing capacity of the lubricant. Approximately 1 or 2 days' worth of passing cars is needed to bring the wheel rail noise generation back to that observed prior to applying the lubricant. The slow grease dry-out reaction appears to depend on weather conditions after the lubricator is turned off.

TEST DESCRIPTION

Background Information

The acoustic data described in this report were collected June 7–18, 2004. During this time, the weather was mixed in the Portland area. During the first 7 days of work, the temperatures hovered around 55-65 degrees. There were heavy rains just prior to the start of test. During this time the lubricators were shut off so that the rail surfaces would be thoroughly dry before restarting them for the test. This condition resulted in the track being fairly clean at the start of the test. As a result, the noise observed during the first few days was less than that observed prior to the initiation of the last three lubricants tested. It's not clear why this was the case, but possibly the earlier heavy rain provided the special "dry" track conditions at the start of testing. Table 3 of Annex D reveals this observation for lubricant "A."

The test site selected by the TTCI and the TriMet personnel was the northern end of the yellow line, which had recently opened. This site is between a major highway and an access road that leads to the area Expo Center parking lot. The background noise at this location is about 80 decibels plus or minus a couple of decibels. On occasion some trucks, cars, and airplanes from the

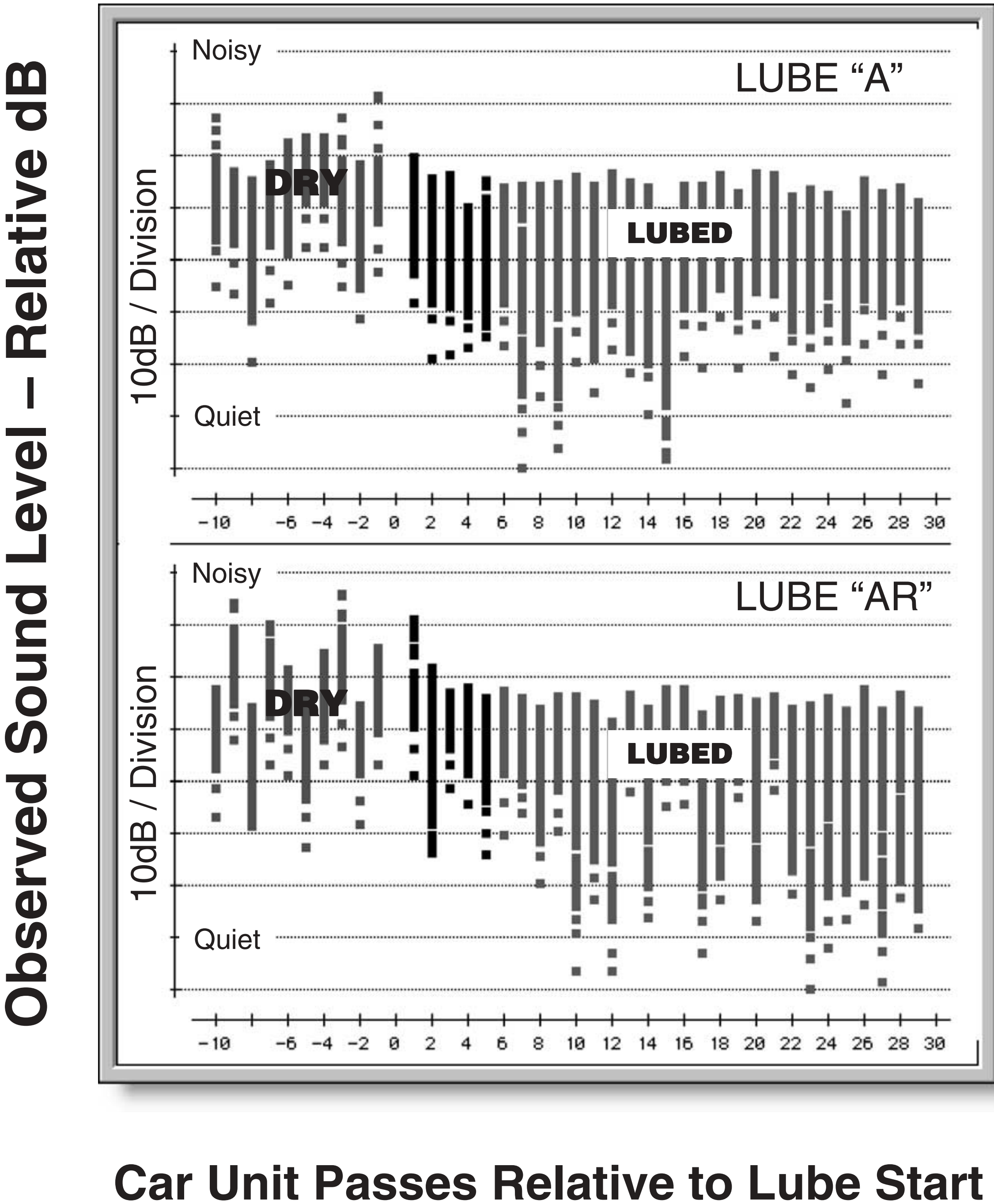


Figure 4—Plots of observed sound levels for lubricants "A" & "AR."

nearby Portland International Airport create noise that overlapped with a few passing transit cars. In most cases, however, the passing transit units generated sufficient noise to exceed the normal ambient background level. Loud car noise levels allowed for the identification and separation of car noise character from the ambient lower-level random background noise. Visual graphics from high-level transit vehicle noises, as well as very low noises generated by some cars, are displayed in the main body of this report. See Figures 13 through 16.

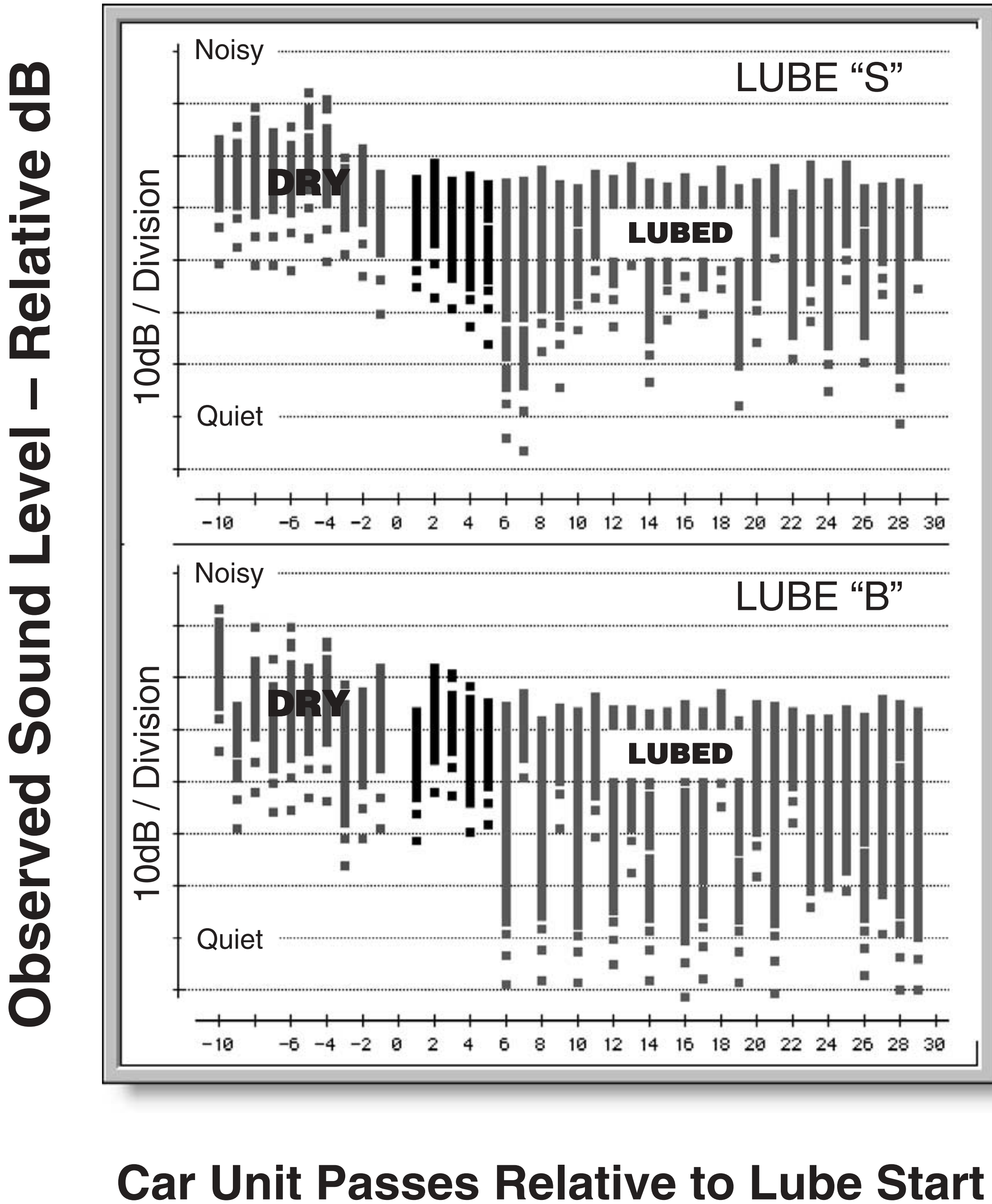


Figure 5—Plots of observed sound levels for lubricants "S" & "B."

Ambient Temperature

Hourly temperatures are recorded at the Portland airport at all times. These data are archived by the national weather bureau. The hourly data were collected over the Internet and listed along with the times of passing cars throughout the period of data collection.

Ambient temperature variations during the test varied widely, typically from a low of 55 degrees to over 90 degrees Fahrenheit. Temperatures during the first 7 days ranged from 55 to 65 degrees. During the last 3 days of testing, the temperatures rose rapidly in the mornings from 60 to 65, and, during the last day, they went above 90 degrees Fahrenheit. Plots in Figure 6 show the range of temperatures that occurred during each test day, as well as the hourly swings that occurred.

Passing Car Units

Every 9 minutes, a transit car passed the test site throughout the duration of the study. The sounds from 434 car units (a typical car unit is a pair of cars called a "consist") were recorded over a 10-day period. The majority of passing car units were actually two cars paired up to make a full consist. Occasionally a single car went by. Approximately 90 percent of the car units passing the recording site were dual-car consists.

This report will use the term "car unit" to imply either a single passing car or a dual pair without distinction. No category was prepared in the database for identifying single car passes that occurred during test. However, extensive voice notes were made after every car unit passed, and this test condition could be established if needed.

Although a car unit was observed to pass the recording location every 9 minutes, the elapsed time between cars actually varied from about 1 minute to over 20 minutes. A histogram of the time between car units recorded is shown below in Figure 7. The total time spent trackside recording passing vehicles was just over 65 hours. A tabulation of the all-car units passing through the site by car number and their frequency of occurrence is provided in Table 1.

Distance To/From Rail Lubricators

The selected test site was convenient for recording the same car units moving in two directions. Since the test location was near the end of the line, cars going in one direction had to pass in the other direction immediately after going north. The arrangement was such that each car had to pass over a lubricator every time it passed the test site. One lubricator was approximately 200 feet south of the test site. Another lubricator was approximately 1,200 feet north of the test site. Therefore, northbound cars were anticipated to have more lubricant on their wheels than southbound cars since the northbound cars had a shorter distance to go before reaching the test site.

Overview of Acoustic Data Collection

The acoustic recording operation used three separate microphones. A display of the arrangement is shown in Figure 8 displayed below.

A reference sound level meter was placed at the center of the two tracks going north and south. On either side of the north and southbound tracks stereo microphones were placed. The stereo microphones were positioned approximately 6 to 7 feet away from the outer rail of the transit tracks. The center reference microphone was approximately 4 feet from the inner rail of each track. The centrally located microphone was about 20 inches above the TOR, whereas the field microphones were about 15 inches above the TOR. Specifications for each microphone used during testing are provided in Annexes A and B. Wires ran directly from the centrally located microphone to a test computer. The field side microphones contained their own independent digital storage for continuous sound recording and were turned on and off at the beginning and end of each test day.

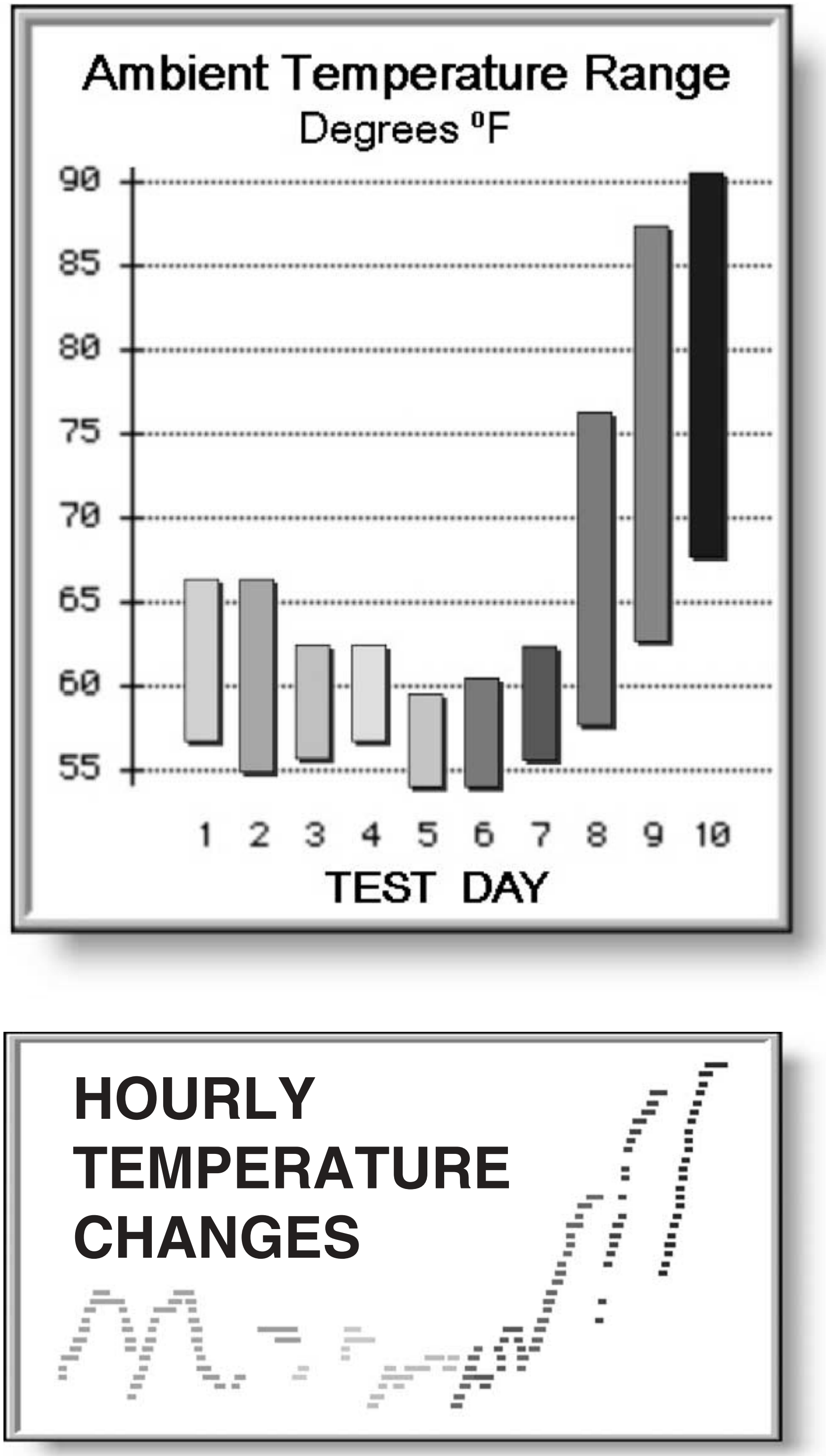


Figure 6—Displays of temperature ranges observed during study.

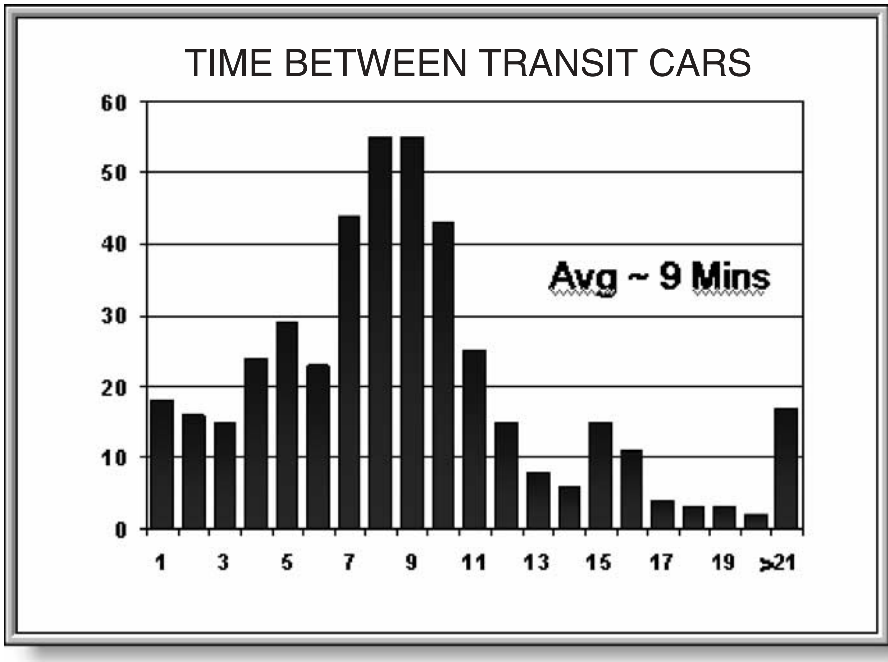


Figure 7—Histogram of time between transit cars observed during study.

Pictures of the reference sound level meter used in recording the sounds from passing car units are shown in Figure 9. The close-up image is for documentation of the instrument switch settings used in capturing acoustic data directly by computer. Similarly, Figure 10 shows the faceplate of one of the field side stereo microphones used during testing. The field side microphones collect continuous sound throughout the day. The digital form of the acoustic information stored in the stereo field side microphone's flash memory was archived each evening. The total data storage from the two field side recording units is approximately 10 gigabytes.

The majority of the test data and the summary information presented in this report are derived from the reference microphone placed between the two site location tracks. Corroborative acoustic information from the field side microphones is available as needed. Several time-based sound signatures from the center recording microphone are shown below. It takes approximately 5 to 10 seconds for a transit vehicle to pass the line of three recording microphones, depending upon the speed of the vehicle going by the site. In most cases, 30 to 40 seconds of data were recorded for each passing car unit. This provided 10 or 15 seconds of extra recorded information on either side of the passing vehicle, which normally was extra unused information. The unused portion of each recording, however, provided some insight on the background noise available at the test site during various car passes. Available on tape are clear sounds from passing motorcars, trucks, buses, airplanes, and even birds in the trees near the microphones. The site was across the street from a bird sanctuary.

At the start of some test days, calibration information from the microphones was collected for future reference. Calibration of the reference microphone located between the northbound and southbound tracks consisted of placing a pistophone over the microphone barrel and recording its output voltage signal directly to computer. In addition, a "reference voltage signature," which

Table 1—Total number of times each car passed site.

ROW	CAR ###	~PASSES	% OF PASSES	CUM % PASSES
1	301	27	6.2	6.2
2	313	26	6.0	12.2
3	222	25	5.8	18.0
4	226	25	5.8	23.7
5	317	25	5.8	29.5
6	310	24	5.5	35.0
7	312	23	5.3	40.3
8	306	22	5.1	45.4
9	203	21	4.8	50.2
10	308	19	4.4	54.6
11	302	18	4.1	58.8
12	309	18	4.1	62.9
13	318	17	3.9	66.8
14	311	16	3.7	70.5
15	315	15	3.5	74.0
16	305	15	3.5	77.4
17	303	11	2.5	80.0
18	304	8	1.8	81.8
19	234	8	1.8	83.6
20	202	7	1.6	85.3
21	316	6	1.4	86.6
22	210	5	1.2	87.8
23	212	5	1.2	88.9
24	252	5	1.2	90.1
25	307	5	1.2	91.2
26	250	4	0.9	92.2
27	110	4	0.9	93.1
28	248	4	0.9	94.0
29	233	4	0.9	94.9
30	216	3	0.7	95.6
31	219	3	0.7	96.3
32	314	3	0.7	97.0
33	206	2	0.5	97.5
34	103	2	0.5	97.9
35	204	2	0.5	98.4
36	240	2	0.5	98.8
37	225	2	0.5	99.3
38	237	1	0.2	99.5
39	255	1	0.2	99.8
40	324	1	0.2	100.0

is generated by the internal electronics of the sound level meter itself, was recorded to hard disk. This method of calibration provides a total throughput check on the microphone and wiring set-up. At calibration time the acoustic levels are confirmed to be heard, processed, carried through all connecting wiring, and properly stored by the computer at known reference levels. A sample calibration and reference signal from 1 day's recording is displayed here in Figure 11.

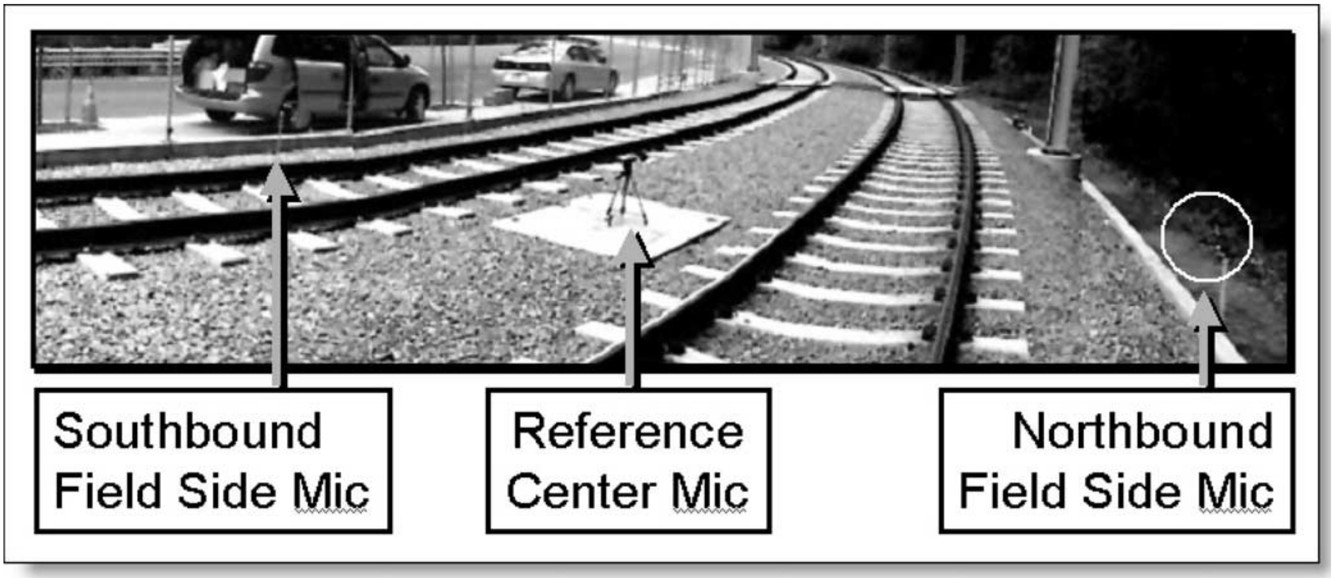


Figure 8—View of microphones used during study displaying their relative locations.

Sample Time-Based Signatures

A couple of typical time-based signatures are presented in Figure 12 for visual review. One was collected while the rails were dry and the other was collected when the track was fully lubricated.

Sample Tabular Data

Subsequent to collecting the data in Portland, the recorded acoustic files were processed. Various quantities of frequency information were analytically extracted and then tabulated. The first 18 columns of the table are shown in Annex C. In addition to the columns shown in Annex C there were actually 117 more columns included in final data table. These 117 extra columns not listed in the tabular information of Annex C contain the frequency character of the passing cars. Annex C is a compilation of the collected information that provides all the operating test conditions of each recording listed row by row. Each table heading shown in Annex C is explained more thoroughly in the itemized list of Table 2.

Special Comments on Acoustic Data Processing

A few comments need to be made about the present set of acoustic data and how it relates to the review. There are many ways to review and interpret common time-based signatures of sound. The majority of the acoustic data in this report are interpreted on the basis of the spectral magnitude and character of each passing car. In particular, the spectrum of each passing car contains 114 separate frequency bands (measures of amplitude or sound pressure levels, if you will). The 114 frequency band amplitudes come from performing the standard 1/24 octave analysis on the data. If we really want to know the amplitude of the passing car sounds we must also ask, "What is the frequency range of the amplitudes I am concerned about?"

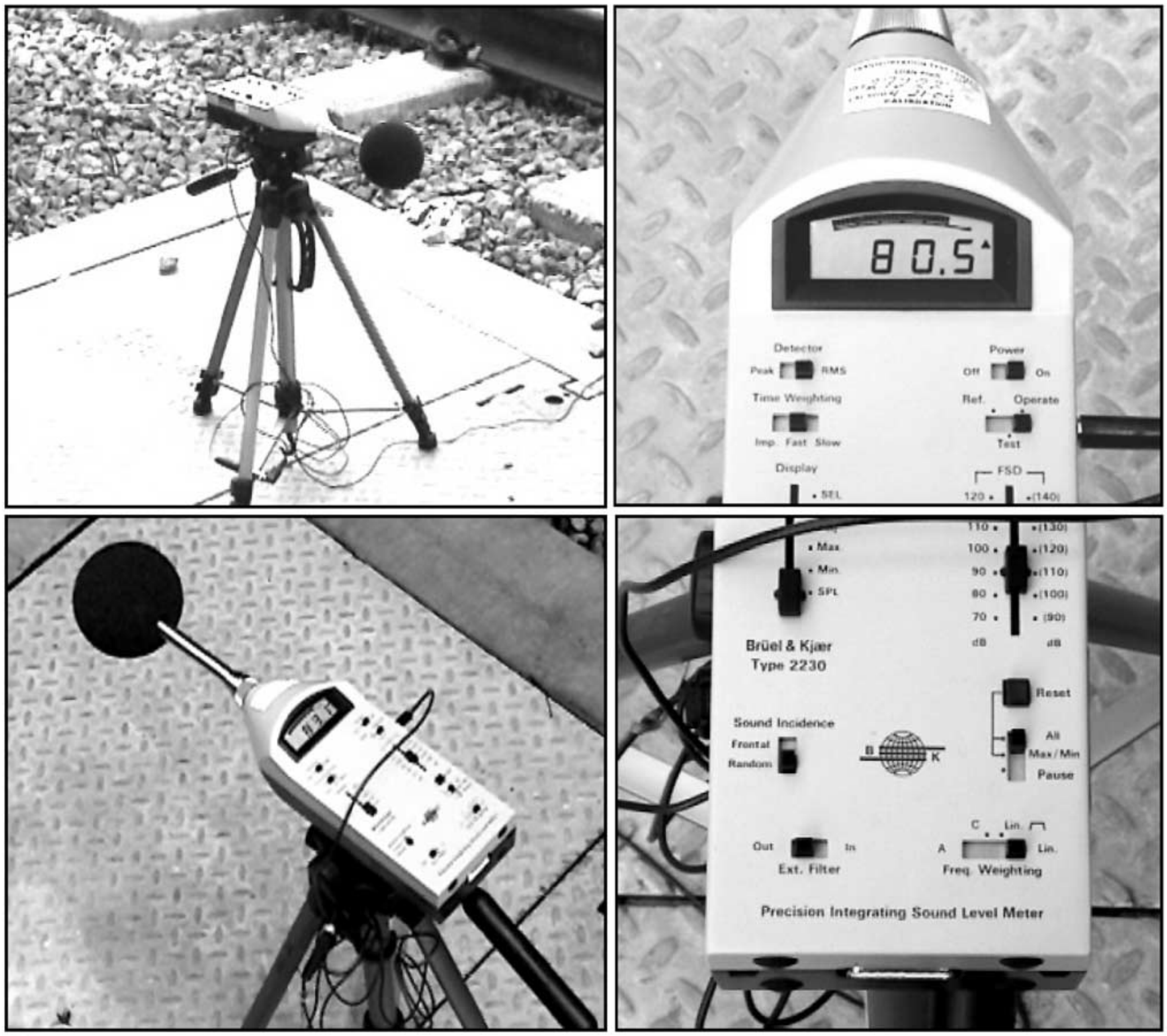


Figure 9—Images of the sound level meter placed between the northbound and southbound tracks.

In addition, sound spectra are normally plotted on a decibel log scale basis. Since most sounds found throughout nature cover several decades of amplitude, it is customary to review acoustic amplitudes using log scales. So, all the sound magnitude displays in this report use common base 10 log scales on their vertical axes. Since all sounds are relative in nature, all sound magnitude plots in this report use relative log-based decibel vertical scales. All report displays of sound magnitude are relative in nature and cover similar scales, and comparisons among the various sound magnitude plots can therefore be performed by inspection. The ability to directly compare plots derived under various operating conditions is one of the most important benefits of this acoustic evaluation output.

Figure 10—Image of stereo microphone recorder deployed outside of both tracks during study.

Acoustic Sampling

A spectrum was plotted from every one of the 434 recordings of passing transit car units. The spectra and 1/24 octave band sound level summaries fully represent the sound frequency content of each passing car unit (note: each representative spectrum was created from only the "nearby" passing car portion of the full acoustic recording). Each spectrum contains 114 separate frequency bands or numeric values. The spectrum values from each recorded car unit were placed in its own distinct row of an extensive tabular file, an extended version of the table shown in Annex C. This report file contains approximately 50,000 frequency-based values. Most elements that make up the table are frequency band amplitudes that characterize all the test cars observed.

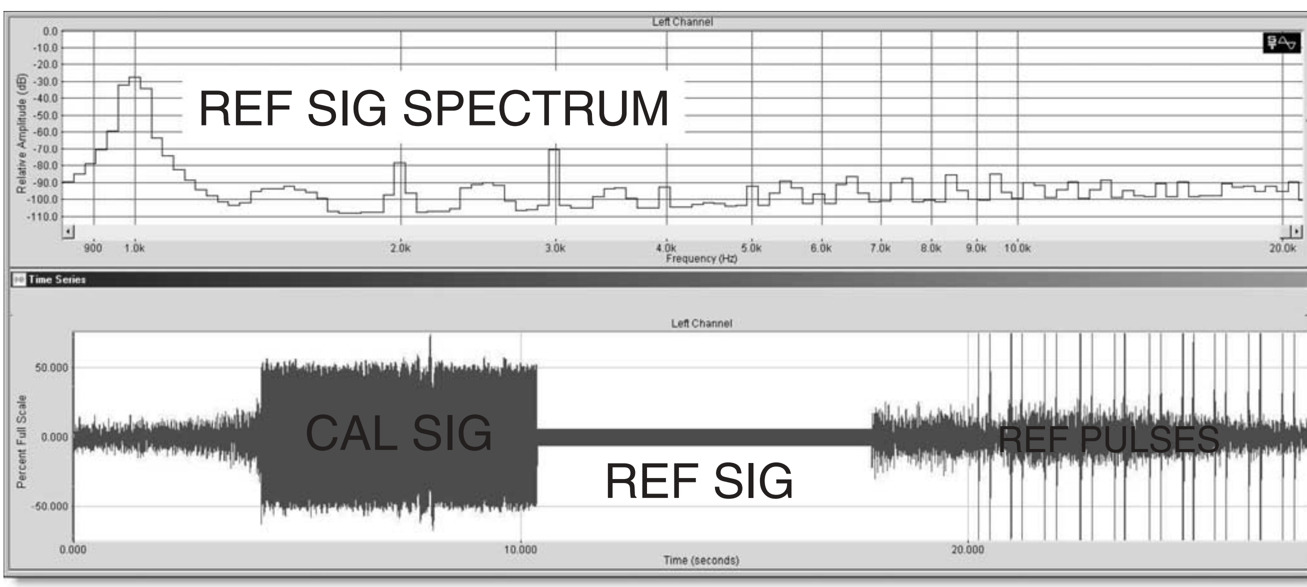
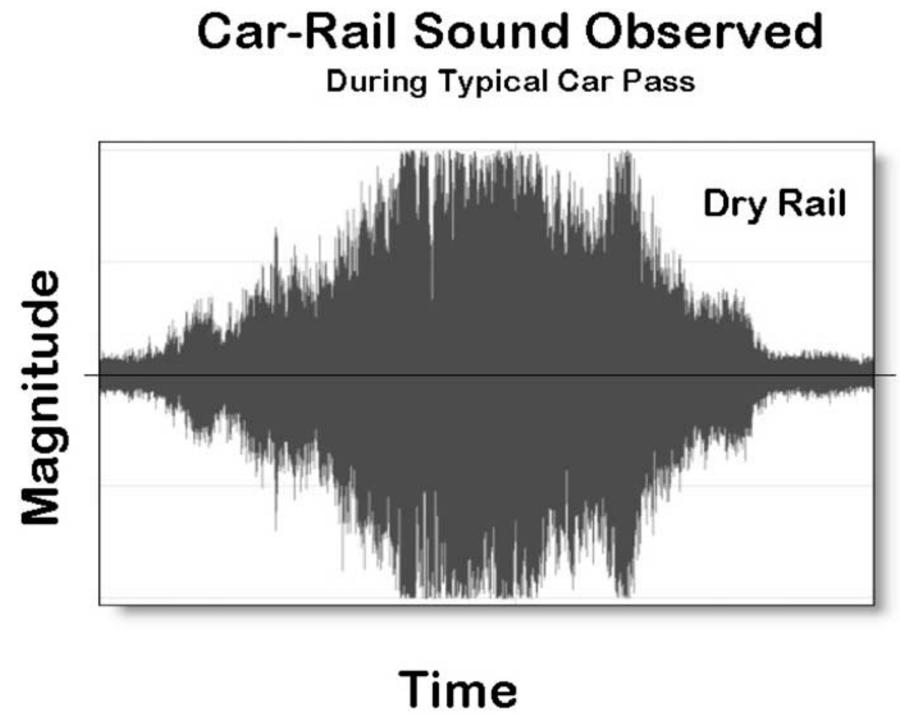


Figure 11—Sample calibration and reference signals with spectrum collected.



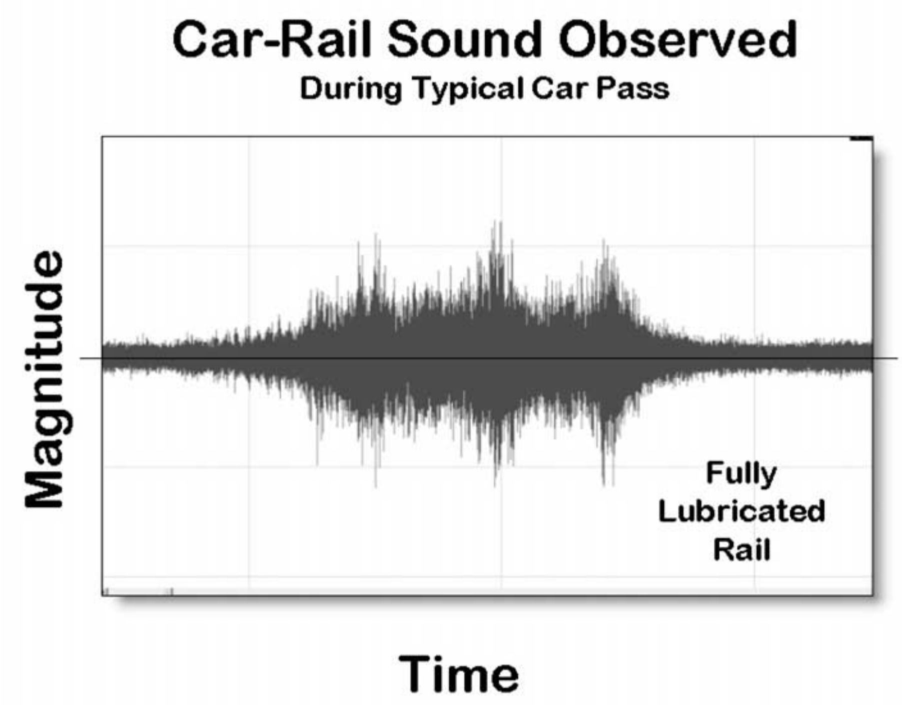


Figure 12—Typical time-based noise recordings taken on dry and lubricated rail.

The remainder of the table contains the operating test conditions at the time of the recording. Again, see Annex C for the operating test conditions portion of the tabulated data.

Since acoustic data are typically collected at a rate of 44,100 samples per second for about 40 seconds, there is a total file storage of 770 million sound bits of information just from the centrally

Table 2—Description of table headings used in Annex C.

DATA TABLE HEADINGS DEFINED		
COLUMN	HEADING	DESCRIPTION
1	ROW	TABLE ROW
2	CAR_1	CAR NUMBER OF FIRST CAR IN CONSIST
3	CAR_2	CAR NUMBER OF SECOND CAR IN CONSIST
4	CON#	CONSIST NUMBER
5	ON - OFF	LUBRICATOR ON OFF CONDITION
6	NB - SB	CODE FOR NORTHBOUND OR SOUTHBOUND TRAFFIC
7	DATE	DATE OF CAR PASS
8	TIME	TIME OF DAY OF CAR PASS
9	HOUR	HOUR ONLY OF THE CAR PASS
10	MINS	MINUTES ONLY OF THE CAR PASS
11	CUM_HRS	CUMULATIVE HOURS FROM START OF DAY
12	DEL_MINS	TIME IN MINUTES SINCE LAST CAR RECORDED
13	DEGS F	AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT
15	RAIN wmd	WET WEATHER CODE: WET -- MISTY -- DRY
16	PASS #	CAR PASS NUMBER RELATIVE TO START OF LUBRICATOR
17	LUBE	LUBRICANT CODE: A - AR - B - S
18	DAY #	NUMBER OF TEST DAY FROM START OF TEST
19	SPCAVGRLTV-DB	SIMPLE AVERAGE OF SPECTRUM BAND VALUES IN RELATIVE DB

located microphone used in testing. With 434 passing car units, this works out to be approximately 1.75 million acoustic data points available for creating each spectrum of each passing car unit. Each sound bit is stored with a 24-bit accuracy, which means that the central microphone alone gathered over 18 gigabytes of acoustic information.

Extreme Time-Based and Spectrum Plots from Passing Cars

Figure 13 is a combination graphic that shows a time-based signature along with the corresponding acoustic spectrum. Note the stair-stepped nature of the spectrum. This is the nature of octave-based analyses. The image shown in this figure is taken from one of the passing car units and is an unusually loud one; it even shows a slight over range and the signature itself clipped off at the highest amplitudes. The majority of sound signals collected during this study had no clipping whatsoever. Also note the bumpy or peaked nature of the spectrum. The presence of these peaks implies that the generated noise most likely contains some resonating mechanical elements. When this happens, acoustic energy is concentrated near a few of the cars' mechanical structures' resonating frequencies, and those particular frequencies are accentuated.

Conversely, when a passing car is relatively quiet or has been well lubricated, the potentially excitable mechanical elements of the car are not highly activated. The noise energy is spread out through all of the spectrum frequencies and the spectrum itself tends to be flatter. An example of this is shown below in Figure 14.

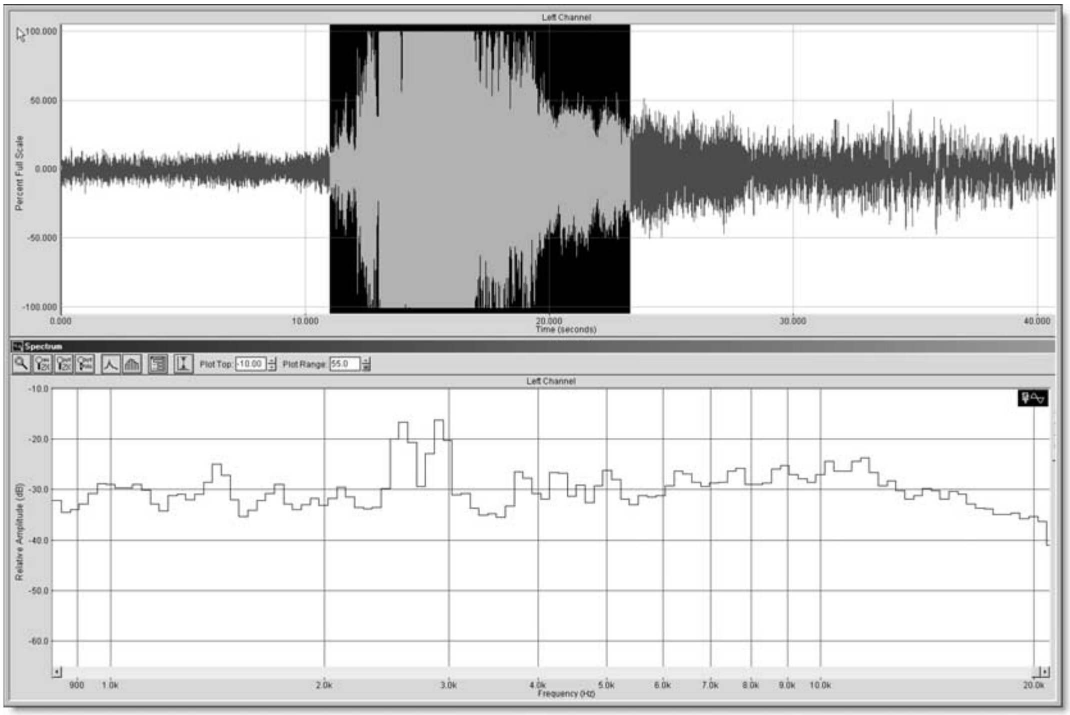


Figure 13—Sample view of extremely noisy signal with spectrum. Note unusual clipping.

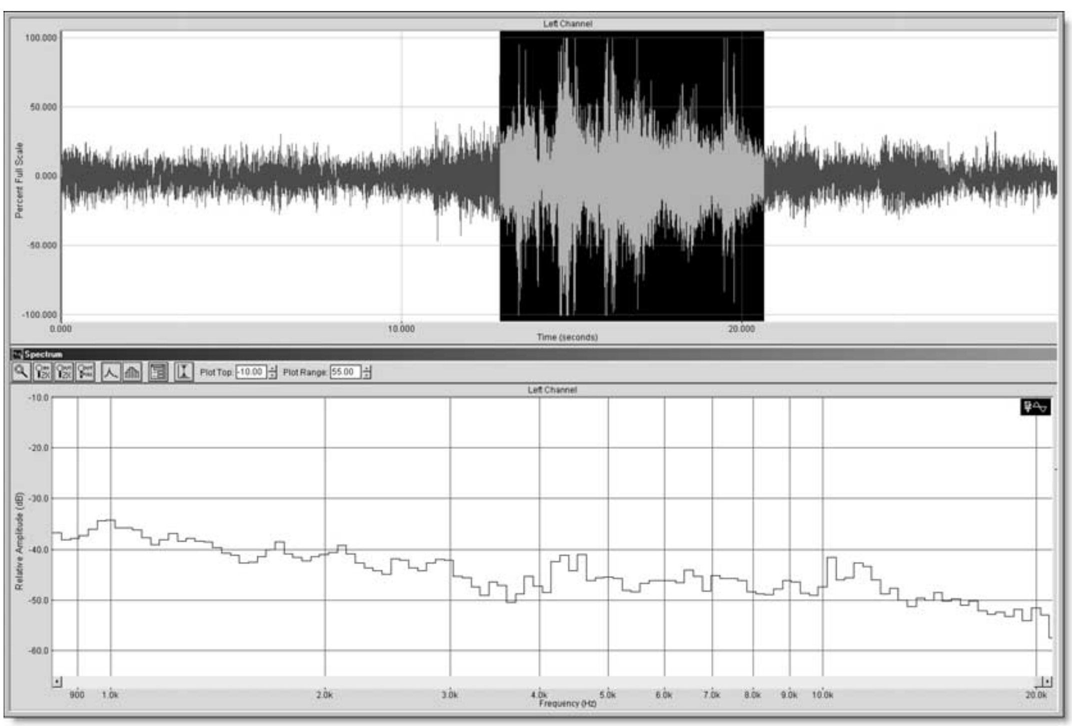


Figure 14—Sample view of nominally quiet signal with spectrum.

Examples of nominal signatures from passing cars are given in Figures 15 and 16. These examples show average signature structures when the track was dry and lubricated, respectively. Note in the dry example that there is some spectral peak character. But in the lubricated case, the spectrum tends to be flatter in nature and has a lower magnitude in the high-frequency portion of the spectrum.

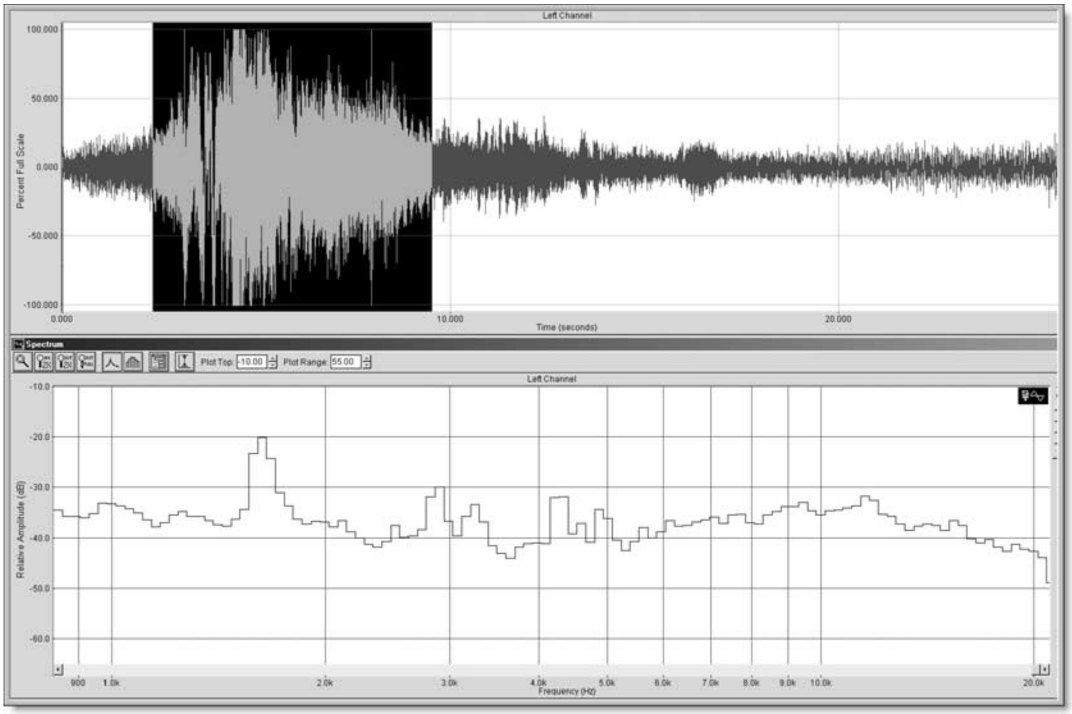


Figure 15—Typical noisy signature and spectrum from car on dry rail.

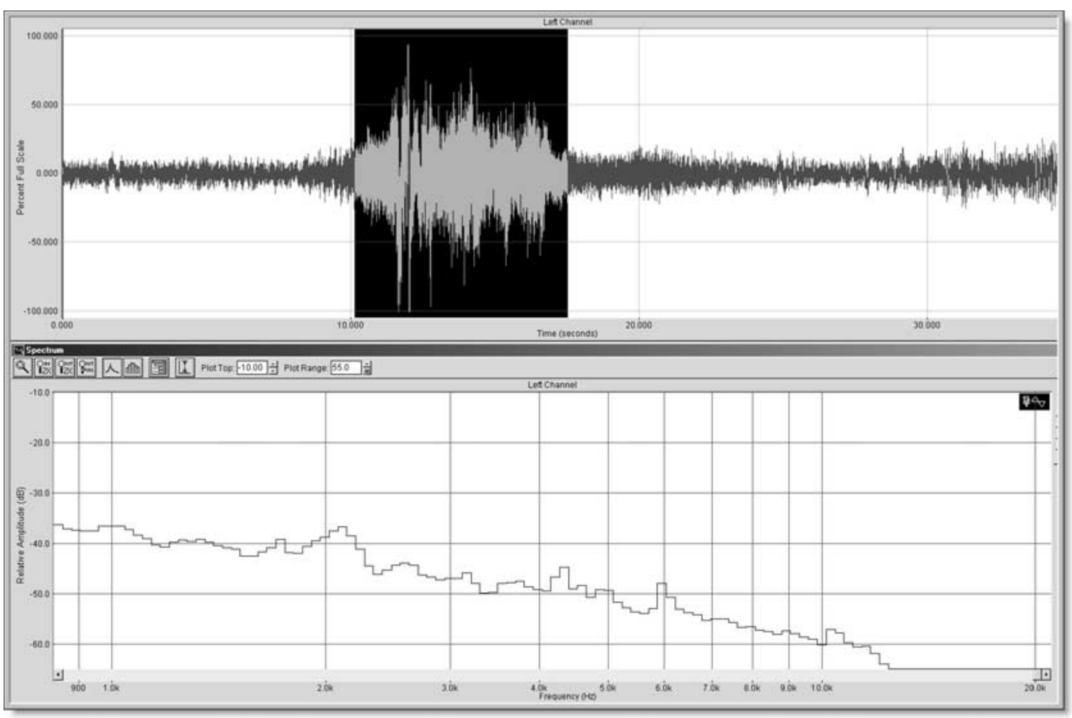


Figure 16—Typical quiet signature and spectrum from car on lubricated rail.

Once a 1/24 octave-based spectrum is created from a selected portion of the time-based signature, a table of numeric values that make up that spectrum is then obtained. There are 114 data elements that make up the stair-stepped spectrum shown in these figures. These stepped values are averages for the frequency band tabulated directly below each step on the X-axis part of the plot.

Test Lubricants

A performance objective of this test is to determine if different types of lubricants vary capacity to reduce noise. Four separate lubricants were applied to the rails during the study. The various lubricants came in black, brown, white, and khaki green and were derived from various lubricant base materials. The four lubricants were identified by the manufactures and coded for testing as follows as:

1) Soybean Version “A” . . . . .Coded in this report as “A”
2) Synthetic Lubricant . . . . .Coded in this report as “S”
3) Biodegradable Lubricant . . . . . .Coded in this report as “AR”
4) Soybean Version “B” . . . . .Coded in this report as “B”

A closeup of a bead of grease is shown in Figure 17. A picture of the tubes leading to the lubricator, as well as a view of the bead of grease on top of the rail, is displayed in Figure 18.

Figure 17—TOR at point of lubrication showing extruded bead of grease.

Figure 18—TOR at point of lubrication showing pressure feed tubes leading to rail.

The noise response to the presence of the individual lubricants on the rail was previously shown in several figures. One thing should be noted about the four sound displays that represent the individual lubricants. The temperature varied widely during some days of testing. In fact, it was very hot during the last 3 days of testing, whereas the first 7 days were moderately warm. It was surprising that the last lubricant tested (lubricant "B") doesn't show a dramatically different response than all of the other fluids tested, just on the basis of temperature change. This last lubricant was evaluated when the temperature exceeded 75 degrees Fahrenheit. The first lubricant (lubricant "A") was reviewed when the temperature was near 60 degrees Fahrenheit. Yet both the first and last lubricants (and even the other two) provide approximately the same acoustic response. Refer back to Figures 4 and 5 for a review of the separate lubricant-dependent characteristics of the recorded car noises.

Differences in Sound Levels Between North and South Traffic

Figure 19 is an overall view of all data collected—plotted against the relative number of passing cars. Negative numbers in the plots represent cars that went by just prior to when the lubricator was turned on. Positive numbers represent cars that passed just after turning the lubricator on. Note the dramatic drop in sound level just after the lubricator was turned on. The acoustic transition from dry to lubed acoustic response takes only 5 to 10 passing car units to develop. Once the lubricator is on, the impact of the lubricant on the character of the noise is impressive. After only a few car units pass over the TOR lubricator, the noise begins to drop off.

To see this same information in a different light, refer again to the middle portion of Figure 19. The middle portion of the figure represents only the data collected from the southbound transit cars. Alternatively, the lower portion of the graphic in the same figure represents the data collected from just the northbound cars.

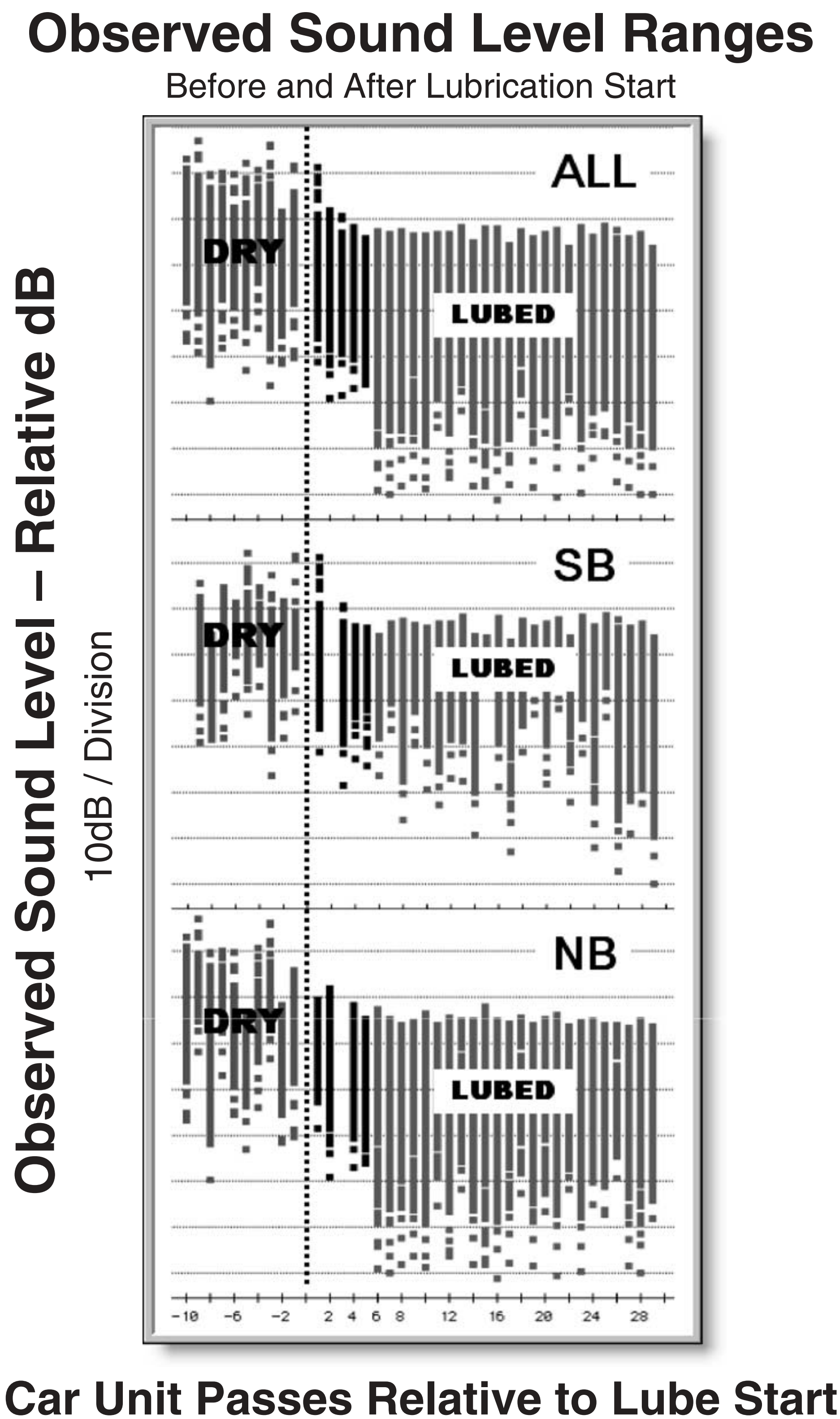


Figure 19—Comparison views of sound level signals from northbound (NB) and southbound (SB) traffic.

In general, it can be said that the southbound signatures were lower during the dry rail portion of the test and higher for the lubricated portion of the test (that is to say, in relation to the northbound data set presented in the same figure). Some of this observed difference is understandable knowing that the distance from the lubricator on the southbound track was approximately five times farther away than the lubricator on the northbound track. This difference in distance to the separate lubricators, at least for the lubricated condition, implies that the southbound track may not receive as much lubricant at the microphone location as it did on the northbound track over any common time span.

On the other hand, the "dry track condition" shows an acoustic response that is the opposite of the lubricated rail condition, i.e., the southbound traffic appears to be slightly quieter than the northbound traffic throughout the 10-day test. This might be explained on the basis that the lubricant placed on the northbound rail gets carried into the southbound tracks since we were located at the end of the transit line. Therefore, there might be more lubricant available on the southbound rails for a little while longer after the lubricators are turned off and while the lubricants were being switched out for testing. This may actually have been the case, since it is known that some lubricant continued to bleed onto the rail even after the lubricator had been turned off. Apparently, extra internal line pressure or the elevated position of the lubricant source container allows some of the grease to continue until it oozed out onto the rail. So, more lubricant than was desired continued to ooze onto the track even during periods when the track was drying.

In addition to this, there was a crossover track at the end of the transit line near the point of lubrication that caused some cars to pick up double the amount of lubricant from the lubricator positioned on the southbound track. Crossover occurs strictly on a random basis depending upon which of the track station positions are open as cars come into the station at the end of the line.

Additional Reviews of the Collected Acoustic Data

In addition to several graphic plots for analysis, other reviews of the data were performed. Regressive variance analyses were performed on the tabulated acoustic records. Sensitivity analyses related to combinations of all available operating parameters were made in conjunction with the frequency spectral column data recorded. Refer to Annex C for a list of operating parameters that are available for analysis. At various points throughout the body of this report, various points about the lubricants and the operating conditions are made. Here, the most sensitive tests variables and their associated rank order of importance in reducing wheel/rail noise are summarized. The most important parameters include the

1) Presence or lack of lubricant on the rail,

2) Frequency content of the noise,

3) Prevailing weather conditions,

4) Duration of elapsed time since lubrication was added,

5) Distance from the point of lubrication,

6) Nominal level of the ambient temperature, and

7) Type of lubricant used.

The following other factors are known to be important to wheel/rail noise provided by transit cars but were not reviewed or included in the present measurement process as a changing parameter:

1) Speed of the transit car,

2) Specific car in use (i.e., its maintenance condition),

3) Curvature of the track, and

4) Wear condition of the rail.

In the present test, distance from the point of lubrication was intimately related with the direction of travel of the vehicles. So, the direction of travel needs to be interpreted as the distance from the point of lubrication, even though the direction of travel was discussed as being important and was used as an indicator in some reviewed sound level plots.

It was also observed in the study that specific cars on occasion make unusual noises. Although this was not tabulated and used as a variable for sound level evaluation, one should be careful if particularly noisy cars are tested in the future, especially if they dominate the fleet reviewed. In particular, some cars were observed to have clicking sounds emanating from their wheels, which indicates the possible presence of small flat spots or some other anomaly that can create sharp, high-amplitude spectrum peaks in acoustic data. Even though this operating condition was observed occasionally, it was not a dominant condition in the fleet or considered critical to the study—so it was ignored.

In addition to the data collected and reviewed in this report, several hours of voice-annotated notes were collected. These voice notes contain timestamps and can be related to each car pass as desired. If for some reason future questions arise relative to specific study conditions, these notes can be reexamined and will be retained for review.

Figure 20 contains six extra photos taken during the study. One of the images provides a close-up of the TOR where some lubricant had solidified on the edge of the loaded surface portion of the rail. This photo was taken at a location that was approximately 200 feet north of the northbound lubricator.

CONCLUSIONS AND RECOMMENDATIONS

The following major conclusions can be drawn from the data gathered for this report.

- Of the operating parameters reviewed, the placement of a bead of lubricating grease at a fixed point on a transit rail is one of the most important factors in effectively reducing car/rail noise beyond the point of lubrication. See Figure 3 in the main body of this appendix.

- From a noise reduction standpoint, no single lubricant evaluated in this study is any more effective than another. Each tested lubricant is an effective reducer of acoustic noise generated by transit cars when the lubricant is present on the rail. See Figures 4 and 5 in the main body this appendix. Also see Figures 21 and 22 and Table 3 in Annex D.

Figure 20—Composite of several extra photos taken during study.

- The relative noise reduction attained by all the tested lubricants is in the range of 10 to 20 decibels. The amount of sound level reduction depends strongly upon the frequency (i.e., sound pitch) of the noise generated. The higher-frequency components of the generated noise are reduced the most. This conclusion is from the data displayed in Figure 3 of this appendix and Table 3 in Annex D.

- It only takes 5–10 passing car units to significantly reduce car/rail noise generated beyond a lubricator application point (i.e., when the lubrication point is within 1,500 feet of the observed noise generation region). See Figures 4 and 5 in the main body of this appendix. Also see Figures 21 and 22 of Annex D.

- ❑ The acoustic benefits realized from applying a lubricant to the rail may continue for several days after the lubricator is shut down. Weather conditions dominate the grease dry-out rate. See Annex C (last column).

- ❑ High ambient temperature has a slight noise-reducing affect (mostly on the minimally lubricated rail) and may actually redistribute previously applied lubricant, extending the car/rail noise and reducing benefits of any small amounts of grease present on the rail. This conclusion is from an undisclosed regression analysis of the collected sound data.

In general, this was a very exciting study. It was interesting to find that the presence of small amounts of lubricant effectively reduces the noise of passing transit cars. Although the weather and temperature conditions varied widely, the stability of the noise information attained was remarkable. During the first day or two, it occasionally drizzled and there was mist in the air at times. During the last 3 days, the temperature changed by 40 degrees Fahrenheit or more.

If tests similar to these are ever done in the future, they should include operating parameters that are known to affect noise, but that were not taken into account in the present study. These include speed of the transit car, maintenance condition, tests on several curves, braking tests, longer-term lube build-up effects, distance-carrying effects and wash-off resistance of greases, and tests at sites containing both new and worn rail. It might also be good to evaluate rail that is manually cleaned after each grease is reviewed.

Extended acoustic tests could be performed automatically for long periods of time, possibly for months or a year. Portable computer-accessed acoustic recorders can be placed at any location in the transit system and/or moved periodically throughout an extended study. These portable remote acoustic monitoring systems can be set up and accessed with the aid of the Internet (or phone lines) from any transit control center office if desired.

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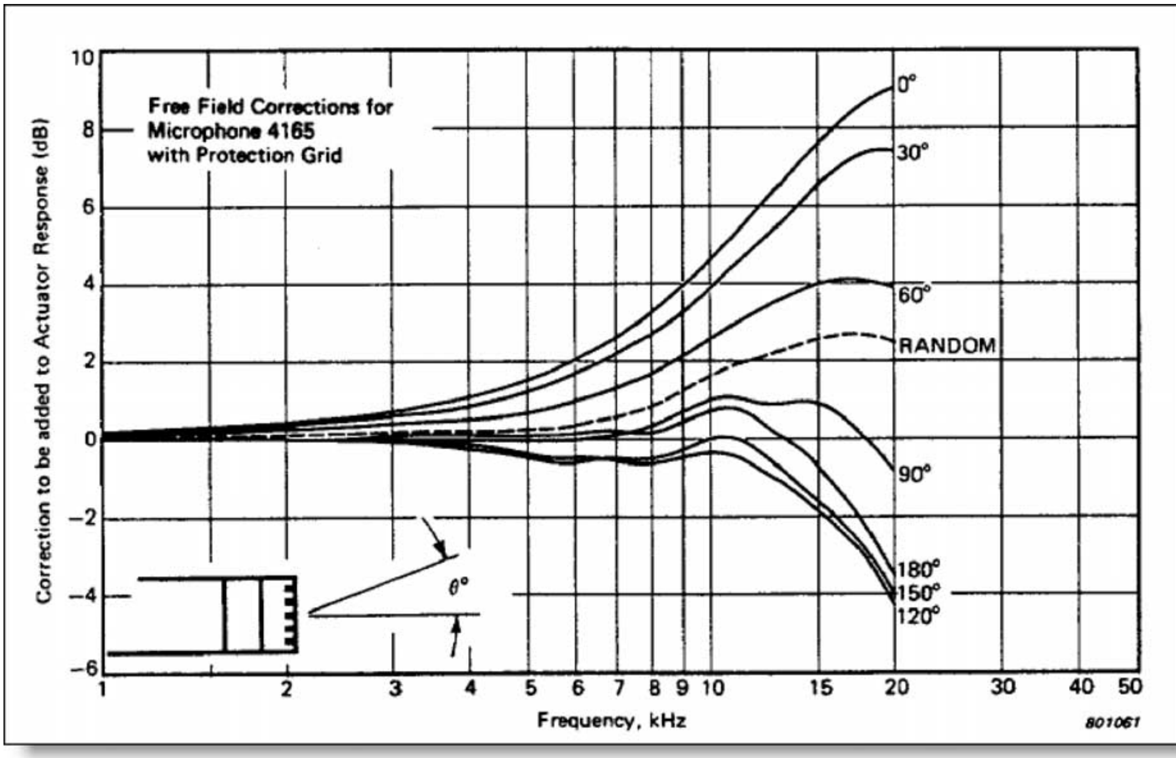
ANNEX A—SOUND LEVEL METER & MIC SPECIFICATIONS



Meter SN#1698908
Calibrator SN#1712214

ANNEX B—STEREO RECORDER & MIC SPECIFICATIONS

Model	ICD-BM1VTP
Mic Jack	Yes
PC Connectivity	USB & Memory Stick Media
Battery Life	Play 12 Hrs/Record 10 Hrs
Dimensions (WxHxD)	1-5/8" x 4-13/16" x 3/4"
Weight	3.5 oz

Sony's ECM-DS70P Electret Condenser Stereo Microphone is a high quality microphone for recording on Digital Media such as MiniDisc, DAT and NT Recorders. The ECM-DS70P features plug in power operation, uni-directional stereo recording, direct connection to recorder, gold plated plug, small sized and lightweight.

Specifications

- High Quality Microphone for Recording on Digital Media such as MiniDisc (MD), DAT, and NT, for recordings with low noise, wide frequency response and dynamic range
- Plug-In Power Operation needs no battery and ensures dependability under virtually all conditions
- Uni-directional Stereo focuses on L and R channel sound originating in front of the microphone while minimizing surrounding sounds, and is an excellent choice for recording vocalists and solo or ensemble instrument performances
- Direct Connection to Recorder provides for faster, easier recording session set-ups
- Small Size and Lightweight (10g) makes this a handy companion for any recording application
- Silver Color matches MiniDisk components
- Reliable Electret Condenser Technology for tried and true performance
- Supplied Microphone Cord (3.3 ft/1m) and Clip provides flexibility in placement, delivers excellent, clear sound signal and helps to avoid motor noise
- Gold Plated Plug for maximum conductivity, minimum noise
- Type: Electret condenser microphone
- Directivity: Uni-directional stereo
- Frequency Response: 100-15,000Hz
- Sensitivity: -38dBV, ±3.5dB
- Noise Level: 34dB SPL
- Maximum Input Level: 110dB SPL (THD 1% @ 1kHz)
- Cord length: 3.3 feet (1m)
- Plug: L-shaped gold-plated mini plug, 3.5mm
- Dimensions(WxHxD): Approx. 2 1/4" x 2 1/4" x 5/8" (58 x 57 x 16mm)
- Weight: Approx. 3/8 oz. (10g)

ANNEX C—TABLE OF TEST CONDITIONS

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPC AVG RLTV-DB
1	255	0	0	OFF	NB	6/7/2004	10:06 AM	10	6	0.00	0	57	D	-70	A	1	-42.045
2	234	317	24	OFF	SB	6/7/2004	10:14 AM	10	14	0.13	8	57	D	-69	A	1	-41.482
3	312	222	22	OFF	NB	6/7/2004	10:17 AM	10	17	0.18	3	58	D	-68	A	1	-41.324
4	307	250	26	OFF	SB	6/7/2004	10:30 AM	10	30	0.40	13	59	D	-67	A	1	-49.616
5	318	306	21	OFF	NB	6/7/2004	11:06 AM	11	6	1.00	36	59	D	-66	A	1	-42.414
6	312	222	22	OFF	SB	6/7/2004	11:12 AM	11	12	1.10	6	59	D	-65	A	1	-43.263
7	317	234	24	OFF	NB	6/7/2004	11:20 AM	11	20	1.23	8	59	D	-64	A	1	-40.941
8	318	306	21	OFF	SB	6/7/2004	11:28 AM	11	28	1.37	8	60	D	-63	A	1	-41.061
9	250	307	26	OFF	NB	6/7/2004	11:38 AM	11	38	1.53	10	60	D	-62	A	1	-48.681
10	317	234	24	OFF	SB	6/7/2004	11:42 AM	11	42	1.60	4	60	D	-61	A	1	-48.936
11	312	222	23	OFF	NB	6/7/2004	11:50 AM	11	50	1.73	8	61	D	-60	A	1	-38.622
12	307	250	26	OFF	SB	6/7/2004	11:56 AM	11	56	1.83	6	61	D	-59	A	1	-48.614
13	233	212	27	OFF	NB	6/7/2004	12:06 PM	12	6	2.00	10	61	D	-58	A	1	-46.256
14	312	222	23	OFF	SB	6/7/2004	12:12 PM	12	12	2.10	6	61	D	-57	A	1	-40.776
15	302	310	25	OFF	NB	6/7/2004	12:18 PM	12	18	2.20	6	62	D	-56	A	1	-46.203
16	212	233	23	OFF	SB	6/7/2004	12:27 PM	12	27	2.35	9	62	D	-55	A	1	-41.862
17	306	318	21	OFF	NB	6/7/2004	12:31 PM	12	31	2.42	4	63	D	-54	A	1	-39.819
18	310	302	25	OFF	SB	6/7/2004	12:42 PM	12	42	2.60	11	63	D	-53	A	1	-45.846
19	324	317	24	OFF	NB	6/7/2004	12:48 PM	12	48	2.70	6	64	D	-52	A	1	-39.197
20	318	306	21	OFF	SB	6/7/2004	12:56 PM	12	56	2.83	8	64	D	-51	A	1	-42.784
21	307	250	26	OFF	NB	6/7/2004	1:06 PM	1	6	3.00	10	64	D	-50	A	1	-42.919
22	317	234	24	OFF	SB	6/7/2004	1:10 PM	1	10	3.07	4	64	D	-49	A	1	-40.980
23	222	312	22	OFF	NB	6/7/2004	1:17 PM	1	17	3.18	7	64	D	-48	A	1	-42.451
24	250	307	26	OFF	SB	6/7/2004	1:27 PM	1	27	3.35	10	65	D	-47	A	1	-50.316
25	212	233	23	OFF	NB	6/7/2004	1:38 PM	1	38	3.53	11	65	D	-46	A	1	-43.115
26	312	222	22	OFF	SB	6/7/2004	1:40 PM	1	40	3.57	2	65	D	-45	A	1	-44.331
27	310	302	25	OFF	NB	6/7/2004	1:48 PM	1	48	3.70	8	66	D	-44	A	1	-50.143
28	233	212	23	OFF	SB	6/7/2004	1:56 PM	1	56	3.83	8	66	D	-43	A	1	-43.168
29	318	306	21	OFF	NB	6/7/2004	2:03 PM	2	3	3.95	7	66	D	-42	A	1	-41.939
30	302	310	25	OFF	SB	6/7/2004	2:12 PM	2	12	4.10	9	66	D	-41	A	1	-46.926
31	317	234	24	OFF	NB	6/7/2004	2:18 PM	2	18	4.20	6	66	D	-40	A	1	-44.038
32	306	318	21	OFF	SB	6/7/2004	2:27 PM	2	27	4.35	9	66	D	-39	A	1	-40.692
33	250	307	26	OFF	NB	6/7/2004	2:31 PM	2	31	4.42	4	65	D	-38	A	1	-49.868
34	234	317	24	OFF	SB	6/7/2004	2:41 PM	2	41	4.58	10	65	D	-37	A	1	-40.102
35	312	222	22	OFF	NB	6/7/2004	2:48 PM	2	48	4.70	7	65	D	-36	A	1	-38.673
36	307	250	26	OFF	SB	6/7/2004	2:56 PM	2	56	4.83	8	65	D	-35	A	1	-47.257
37	301	0	0	OFF	NB	6/7/2004	3:02 PM	3	2	4.93	6	65	D	-34	A	1	-42.741
38	233	212	23	OFF	NB	6/7/2004	3:08 PM	3	8	5.03	6	65	D	-33	A	1	-44.738
39	302	310	25	OFF	NB	6/7/2004	3:22 PM	3	22	5.27	14	65	D	-32	A	1	-54.929
40	310	302	25	OFF	SB	6/7/2004	3:41 PM	3	41	5.58	19	65	D	-31	A	1	-44.566
41	234	317	24	OFF	NB	6/7/2004	3:50 PM	3	50	5.73	9	65	D	-30	A	1	-43.488
42	305	0	0	OFF	SB	6/7/2004	3:56 PM	3	56	5.83	6	65	D	-29	A	1	-43.135
43	307	250	26	OFF	NB	6/7/2004	4:02 PM	4	2	5.93	6	65	D	-28	A	1	-44.798
44	301	0	0	OFF	NB	6/7/2004	4:18 PM	4	18	6.20	16	64	W	-27	A	1	-43.218
45	250	307	26	OFF	SB	6/7/2004	4:28 PM	4	28	6.37	10	64	W	-26	A	1	-43.711
46	222	312	22	OFF	NB	6/7/2004	4:29 PM	4	29	6.38	1	63	W	-25	A	1	-47.155
47	301	0	0	OFF	SB	6/7/2004	4:42 PM	4	42	6.60	13	63	D	-24	A	1	-36.203
48	212	233	23	OFF	NB	6/7/2004	4:44 PM	4	44	6.63	2	62	D	-23	A	1	-43.559
49	312	222	22	OFF	SB	6/7/2004	4:48 PM	4	48	6.70	4	62	D	-22	A	1	-31.616
50	310	302	25	OFF	NB	6/7/2004	4:51 PM	4	51	6.75	3	61	D	-21	A	1	-47.199

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
51	233	212	22	OFF	SB	6/7/2004	4:58 PM	4	58	6.87	7	60	D	-20	A	1	-34.998
52	305	0	0	OFF	NB	6/7/2004	5:05 PM	5	5	6.98	7	60	D	-19	A	1	-52.285
53	302	310	25	OFF	SB	6/7/2004	5:08 PM	5	8	7.03	3	60	D	-18	A	1	-35.117
54	318	306	21	OFF	NB	6/7/2004	5:15 PM	5	15	7.15	7	61	D	-17	A	1	-45.526
55	305	0	0	OFF	SB	6/7/2004	5:18 PM	5	18	7.20	3	61	D	-16	A	1	-40.499
56	306	318	24	OFF	SB	6/8/2004	10:15 AM	10	15	7.20	0	55	D	-15	A	2	-42.200
57	226	313	22	OFF	NB	6/8/2004	10:17 AM	10	17	7.23	2	55	D	-14	A	2	-44.356
58	234	317	26	OFF	SB	6/8/2004	10:29 AM	10	29	7.43	12	56	D	-13	A	2	-35.944
59	204	315	23	OFF	NB	6/8/2004	10:33 AM	10	33	7.50	4	56	D	-12	A	2	-44.244
60	313	226	22	OFF	SB	6/8/2004	10:43 AM	10	43	7.67	10	56	D	-11	A	2	-34.970
61	222	312	25	OFF	NB	6/8/2004	10:50 AM	10	50	7.78	7	57	D	-10	A	2	-39.618
62	315	204	23	OFF	SB	6/8/2004	10:59 AM	10	59	7.93	9	57	D	-9	A	2	-40.707
63	301	203	21	OFF	NB	6/8/2004	11:07 AM	11	7	8.07	8	57	D	-8	A	2	-47.406
64	312	222	25	OFF	SB	6/8/2004	11:11 AM	11	11	8.13	4	58	D	-7	A	2	-39.922
65	306	318	24	OFF	NB	6/8/2004	11:21 AM	11	21	8.30	10	58	D	-6	A	2	-39.755
66	203	301	21	OFF	SB	6/8/2004	11:27 AM	11	27	8.40	6	59	D	-5	A	2	-34.562
67	234	317	26	OFF	NB	6/8/2004	11:34 AM	11	34	8.52	7	59	D	-4	A	2	-34.562
68	318	306	24	OFF	SB	6/8/2004	11:42 AM	11	42	8.65	8	60	D	-3	A	2	-39.808
69	313	226	22	OFF	NB	6/8/2004	11:50 AM	11	50	8.78	8	60	D	-2	A	2	-43.698
70	317	234	26	OFF	SB	6/8/2004	11:57 AM	11	57	8.90	7	61	D	-1	A	2	-37.207
71	315	204	23	ON	NB	6/8/2004	12:05 PM	12	5	9.03	8	61	D	1	A	2	-42.366
72	312	222	25	ON	NB	6/8/2004	12:19 PM	12	19	9.27	14	62	D	2	A	2	-45.250
73	204	315	23	ON	SB	6/8/2004	12:28 PM	12	28	9.42	9	63	D	3	A	2	-44.420
74	203	301	21	ON	NB	6/8/2004	12:35 PM	12	35	9.53	7	63	D	4	A	2	-49.590
75	318	306	24	ON	NB	6/8/2004	12:49 PM	12	49	9.77	14	64	D	5	A	2	-48.435
76	301	203	21	ON	SB	6/8/2004	12:56 PM	12	56	9.88	7	64	D	6	A	2	-47.146
77	317	234	26	ON	NB	6/8/2004	1:03 PM	1	3	10.00	7	64	D	7	A	2	-52.228
78	306	318	24	ON	SB	6/8/2004	1:11 PM	1	11	10.13	8	64	D	8	A	2	-49.805
79	222	318	25	ON	NB	6/8/2004	1:21 PM	1	21	10.30	10	64	D	9	A	2	-50.939
80	234	317	26	ON	SB	6/8/2004	1:26 PM	1	26	10.38	5	64	D	10	A	2	-46.245
81	315	0	0	ON	NB	6/8/2004	1:38 PM	1	38	10.58	12	64	D	11	A	2	-50.650
82	313	226	22	ON	SB	6/8/2004	1:41 PM	1	41	10.63	3	64	D	12	A	2	-46.198
83	222	313	25	ON	NB	6/8/2004	1:53 PM	1	53	10.83	12	64	D	13	A	2	-49.170
84	317	234	26	ON	SB	6/8/2004	1:56 PM	1	56	10.88	3	64	D	14	A	2	-50.016
85	301	203	21	ON	NB	6/8/2004	2:04 PM	2	4	11.02	8	64	D	15	A	2	-56.526
86	312	222	25	ON	SB	6/8/2004	2:12 PM	2	12	11.15	8	64	D	16	A	2	-46.243
87	306	318	24	ON	NB	6/8/2004	2:19 PM	2	19	11.27	7	65	D	17	A	2	-46.515
88	203	301	21	ON	SB	6/8/2004	2:27 PM	2	27	11.40	8	65	D	18	A	2	-43.624
89	234	317	26	ON	NB	6/8/2004	2:32 PM	2	32	11.48	5	65	D	19	A	2	-47.447
90	318	306	24	ON	SB	6/8/2004	2:41 PM	2	41	11.63	9	65	D	20	A	2	-43.267
91	313	226	22	ON	NB	6/8/2004	2:48 PM	2	48	11.75	7	66	D	21	A	2	-45.042
92	317	234	26	ON	SB	6/8/2004	2:54 PM	2	54	11.85	6	66	D	22	A	2	-48.684
93	305	0	0	ON	NB	6/8/2004	2:59 PM	2	59	11.93	5	66	D	23	A	2	-49.229
94	305	0	0	ON	SB	6/8/2004	3:08 PM	3	8	12.08	9	66	D	24	A	2	-47.309
95	315	0	0	ON	NB	6/8/2004	3:11 PM	3	11	12.13	3	66	D	25	A	2	-52.233
96	226	313	22	ON	SB	6/8/2004	3:19 PM	3	19	12.27	8	66	D	26	A	2	-44.583
97	312	222	25	ON	NB	6/8/2004	3:33 PM	3	33	12.50	14	66	D	27	A	2	-47.299
98	315	0	0	ON	SB	6/8/2004	3:32 PM	3	32	12.48	-1	66	D	28	A	2	-45.915
99	203	301	21	ON	NB	6/8/2004	3:39 PM	3	39	12.60	7	66	D	29	A	2	-49.761
100	222	313	25	ON	SB	6/8/2004	3:43 PM	3	43	12.67	4	66	D	30	A	2	-47.101

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ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
101	308	0	0	ON	NB	6/8/2004	3:46 PM	3	46	12.72	3	66	D	31	A	2	-50.321
102	308	0	0	ON	SB	6/8/2004	3:56 PM	3	56	12.88	10	66	D	32	A	2	-48.861
103	318	306	24	ON	NB	6/8/2004	3:52 PM	3	52	12.82	-4	66	D	33	A	2	-46.501
104	301	203	21	ON	SB	6/8/2004	4:07 PM	4	7	13.07	15	65	D	34	A	2	-43.703
105	317	234	26	ON	NB	6/8/2004	4:03 PM	4	3	13.00	-4	65	D	35	A	2	-46.941
106	306	318	24	ON	SB	6/8/2004	4:20 PM	4	20	13.28	17	64	D	36	A	2	-44.558
107	305	0	0	ON	NB	6/8/2004	4:21 PM	4	21	13.30	1	63	D	37	A	2	-47.744
108	234	317	26	ON	SB	6/8/2004	4:28 PM	4	28	13.42	7	63	D	38	A	2	-46.058
109	226	313	22	ON	NB	6/8/2004	4:29 PM	4	29	13.43	1	62	D	39	A	2	-46.285
110	305	0	0	ON	SB	6/8/2004	4:43 PM	4	43	13.67	14	62	D	40	A	2	-46.547
111	315	0	0	ON	NB	6/8/2004	4:40 PM	4	40	13.62	-3	61	D	41	A	2	-46.438
112	313	226	22	ON	SB	6/8/2004	4:49 PM	4	49	13.77	9	61	D	42	A	2	-44.780
113	222	312	25	ON	NB	6/8/2004	4:52 PM	4	52	13.82	3	60	D	43	A	2	-49.798
114	315	0	0	ON	SB	6/8/2004	4:57 PM	4	57	13.90	5	60	D	44	A	2	-45.949
115	308	0	0	ON	NB	6/8/2004	5:05 PM	5	5	14.03	8	59	D	45	A	2	-49.044
116	312	222	25	ON	SB	6/8/2004	5:06 PM	5	6	14.05	1	59	D	46	A	2	-46.746
117	252	311	21	ON	NB	6/9/2004	7:55 AM	7	55	14.05	0	58	D	47	A	3	-49.172
118	310	302	25	ON	SB	6/9/2004	8:08 AM	8	8	14.27	13	58	D	48	A	3	-42.806
119	318	0	28	ON	SB	6/9/2004	8:13 AM	8	13	14.35	5	58	D	49	A	3	-46.356
120	313	226	24	ON	NB	6/9/2004	8:25 AM	8	25	14.55	12	58	D	50	A	3	-49.856
121	311	252	21	ON	SB	6/9/2004	8:28 AM	8	28	14.60	3	58	D	51	A	3	-42.832
122	222	312	26	ON	NB	6/9/2004	8:35 AM	8	35	14.72	7	57	D	52	A	3	-50.055
123	226	313	24	ON	SB	6/9/2004	8:40 AM	8	40	14.80	5	57	D	53	A	3	-41.971
124	203	301	22	ON	NB	6/9/2004	8:54 AM	8	54	15.03	14	57	D	54	A	3	-48.533
125	312	222	26	ON	SB	6/9/2004	8:57 AM	8	57	15.08	3	57	D	55	A	3	-42.426
126	309	308	23	ON	NB	6/9/2004	9:06 AM	9	6	15.23	9	57	D	56	A	3	-50.736
127	301	203	22	ON	SB	6/9/2004	9:12 AM	9	12	15.33	6	57	D	57	A	3	-49.340
128	310	302	25	ON	NB	6/9/2004	9:20 AM	9	20	15.47	8	57	D	58	A	3	-47.512
129	308	309	23	ON	SB	6/9/2004	9:27 AM	9	27	15.58	7	57	D	59	A	3	-44.763
130	311	252	21	ON	NB	6/9/2004	9:35 AM	9	35	15.72	8	56	D	60	A	3	-44.015
131	302	310	25	ON	SB	6/9/2004	9:41 AM	9	41	15.82	6	56	D	61	A	3	-45.104
132	226	313	24	ON	NB	6/9/2004	9:48 AM	9	48	15.93	7	56	D	62	A	3	-46.725
133	252	311	21	ON	SB	6/9/2004	9:57 AM	9	57	16.08	9	56	D	63	A	3	-42.744
134	313	226	24	ON	NB	6/9/2004	11:20 AM	11	20	17.47	83	56	D	64	A	3	-47.901
135	311	252	21	ON	SB	6/9/2004	11:27 AM	11	27	17.58	7	56	D	65	A	3	-46.950
136	222	312	26	ON	NB	6/9/2004	11:33 AM	11	33	17.68	6	57	D	66	A	3	-44.353
137	226	313	24	ON	SB	6/9/2004	11:41 AM	11	41	17.82	8	57	M	67	A	3	-46.037
138	203	301	22	ON	NB	6/9/2004	11:50 AM	11	50	17.97	9	57	M	68	A	3	-44.889
139	312	222	26	ON	SB	6/9/2004	11:56 AM	11	56	18.07	6	57	M	69	A	3	-47.842
140	309	308	23	ON	SB	6/9/2004	1:56 PM	1	56	20.07	120	62	D	70	A	3	-39.907
141	252	311	21	ON	NB	6/9/2004	2:03 PM	2	3	20.18	7	62	D	71	A	3	-49.220
142	310	302	25	ON	SB	6/9/2004	2:12 PM	2	12	20.33	9	62	D	72	A	3	-42.560
143	301	203	22	ON	NB	6/9/2004	2:22 PM	2	22	20.50	10	62	D	73	A	3	-51.266
144	311	252	21	ON	SB	6/9/2004	2:26 PM	2	26	20.57	4	62	D	74	A	3	-36.723
145	203	301	24	ON	SB	6/9/2004	2:41 PM	2	41	20.82	15	62	D	75	A	3	-41.420
146	222	312	26	ON	NB	6/9/2004	2:44 PM	2	44	20.87	3	62	D	76	A	3	-52.135
147	312	222	26	ON	SB	6/9/2004	2:54 PM	2	54	21.03	10	62	D	77	A	3	-38.214
148	309	308	23	OFF	NB	6/9/2004	3:09 PM	3	9	21.28	15	62	D	78	A	3	-51.677
149	313	226	24	OFF	SB	6/9/2004	3:18 PM	3	18	21.43	9	62	D	79	A	3	-40.354
150	310	302	25	OFF	NB	6/9/2004	3:32 PM	3	32	21.67	14	62	D	80	A	3	-49.308

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
151	308	309	23	OFF	SB	6/9/2004	3:32 PM	3	32	21.67	0	62	D	81	A	3	-44.020
152	311	252	21	OFF	NB	6/9/2004	3:43 PM	3	43	21.85	11	61	D	82	A	3	-44.915
153	311	310	25	OFF	NB	6/9/2004	3:43 PM	3	43	21.85	0	61	D	83	A	3	-42.070
154	306	0	28	OFF	NB	6/9/2004	3:45 PM	3	45	21.88	2	61	D	84	A	3	-51.236
155	306	0	28	OFF	SB	6/9/2004	3:56 PM	3	56	22.07	11	61	D	85	A	3	-41.878
156	203	301	24	OFF	NB	6/9/2004	4:02 PM	4	2	22.17	6	61	D	86	A	3	-44.802
157	252	311	21	OFF	SB	6/9/2004	4:06 PM	4	6	22.23	4	61	D	87	A	3	-42.829
158	312	222	26	OFF	NB	6/9/2004	4:07 PM	4	7	22.25	1	61	D	88	A	3	-47.350
159	301	203	22	OFF	SB	6/9/2004	4:18 PM	4	18	22.43	11	61	D	89	A	3	-45.805
160	318	0	0	OFF	NB	6/9/2004	4:19 PM	4	19	22.45	1	61	D	90	A	3	-52.349
161	222	312	26	OFF	SB	6/9/2004	4:27 PM	4	27	22.58	8	62	D	91	A	3	-43.952
162	313	226	24	OFF	NB	6/9/2004	4:28 PM	4	28	22.60	1	62	D	92	A	3	-47.813
163	318	0	0	OFF	SB	6/9/2004	4:49 PM	4	49	22.95	21	62	D	93	A	3	-50.092
164	308	309	23	OFF	NB	6/9/2004	4:51 PM	4	51	22.98	2	62	D	94	A	3	-50.084
165	226	313	24	OFF	SB	6/9/2004	4:56 PM	4	56	23.07	5	62	D	95	A	3	-44.420
166	302	310	25	OFF	NB	6/9/2004	4:57 PM	4	57	23.08	1	62	D	96	A	3	-50.803
167	306	0	0	OFF	SB	6/9/2004	5:01 PM	5	1	23.15	4	62	D	97	A	3	-44.036
168	306	0	0	OFF	NB	6/9/2004	5:06 PM	5	6	23.23	5	62	D	98	A	3	-55.223
169	310	302	25	OFF	SB	6/9/2004	5:08 PM	5	8	23.27	2	62	D	99	A	3	-46.400
170	252	311	21	OFF	NB	6/9/2004	5:17 PM	5	17	23.42	9	61	D	100	A	3	-45.957
171	306	0	0	OFF	SB	6/9/2004	5:29 PM	5	29	23.62	12	61	D	101	A	3	-44.325
172	301	203	22	OFF	NB	6/9/2004	5:37 PM	5	37	23.75	8	61	D	102	A	3	-47.856
173	311	252	21	OFF	SB	6/9/2004	5:35 PM	5	35	23.72	-2	61	D	103	A	3	-48.127
174	203	301	26	OFF	NB	6/10/2004	8:35 AM	8	35	23.72	0	57	M	104	A	4	-50.005
175	222	312	24	OFF	SB	6/10/2004	8:39 AM	8	39	23.78	4	57	M	105	A	4	-47.213
176	311	212	22	OFF	NB	6/10/2004	8:53 AM	8	53	24.02	14	57	M	106	A	4	-50.260
177	301	203	26	OFF	SB	6/10/2004	8:57 AM	8	57	24.08	4	57	D	107	A	4	-50.462
178	103	240	23	OFF	NB	6/10/2004	9:06 AM	9	6	24.23	9	58	D	108	A	4	-47.376
179	212	311	22	OFF	SB	6/10/2004	9:12 AM	9	12	24.33	6	58	D	109	A	4	-35.086
180	226	313	25	OFF	NB	6/10/2004	9:20 AM	9	20	24.47	8	58	D	110	A	4	-47.025
181	203	301	26	OFF	SB	6/10/2004	1:28 PM	1	28	28.60	248	59	D	111	A	4	-41.221
182	240	103	23	OFF	NB	6/10/2004	1:33 PM	1	33	28.68	5	60	D	112	A	4	-43.372
183	311	212	22	OFF	SB	6/10/2004	1:41 PM	1	41	28.82	8	61	D	113	A	4	-41.249
184	313	226	25	OFF	NB	6/10/2004	1:50 PM	1	50	28.97	9	62	D	114	A	4	-45.780
185	309	308	21	OFF	NB	6/10/2004	2:04 PM	2	4	29.20	14	62	D	115	A	4	-44.201
186	226	313	25	OFF	SB	6/10/2004	2:11 PM	2	11	29.32	7	62	D	116	A	4	-37.531
187	312	222	24	OFF	NB	6/10/2004	2:19 PM	2	19	29.45	8	62	D	117	A	4	-48.614
188	203	301	26	OFF	NB	6/10/2004	2:40 PM	2	40	29.80	21	62	D	118	A	4	-42.833
189	222	312	24	OFF	SB	6/10/2004	2:43 PM	2	43	29.85	3	61	D	119	A	4	-38.575
190	311	212	22	OFF	NB	6/10/2004	2:47 PM	2	47	29.92	4	61	D	120	A	4	-40.746
191	301	206	26	OFF	SB	6/10/2004	2:55 PM	2	55	30.05	8	61	D	121	A	4	-41.096
192	310	0	27	OFF	NB	6/10/2004	3:00 PM	3	0	30.13	5	61	D	122	A	4	-43.504
193	310	0	27	OFF	SB	6/10/2004	3:07 PM	3	7	30.25	7	61	D	123	A	4	-48.490
194	103	240	23	OFF	NB	6/10/2004	3:10 PM	3	10	30.30	3	61	D	124	A	4	-42.462
195	212	311	22	OFF	SB	6/10/2004	3:18 PM	3	18	30.43	8	61	D	125	A	4	-35.019
196	226	313	25	OFF	NB	6/10/2004	3:21 PM	3	21	30.48	3	61	D	126	A	4	-42.441
197	240	103	23	OFF	SB	6/10/2004	3:31 PM	3	31	30.65	10	61	D	127	A	4	-35.008
198	308	309	21	OFF	NB	6/10/2004	3:33 PM	3	33	30.68	2	61	D	128	A	4	-41.255
199	313	226	25	OFF	SB	6/10/2004	3:45 PM	3	45	30.88	12	61	D	129	A	4	-37.822
200	302	310	25	OFF	NB	6/10/2004	3:57 PM	3	57	31.08	12	61	D	130	A	4	-45.514

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
201	306	202	22	OFF	NB	6/11/2004	8:00 AM	8	0	31.08	0	54	D	-20	S	5	-31.574
202	202	306	22	OFF	SB	6/11/2004	8:11 AM	8	11	31.27	11	54	D	-19	S	5	-29.690
203	309	308	25	OFF	NB	6/11/2004	8:13 AM	8	13	31.30	2	54	D	-18	S	5	-40.159
204	226	313	21	OFF	SB	6/11/2004	8:28 AM	8	28	31.55	15	54	M	-17	S	5	-40.153
205	222	312	24	OFF	NB	6/11/2004	8:29 AM	8	29	31.57	1	55	M	-16	S	5	-47.027
206	312	222	24	OFF	SB	6/11/2004	8:38 AM	8	38	31.72	9	55	D	-15	S	5	-34.056
207	302	318	26	OFF	NB	6/11/2004	8:43 AM	8	43	31.80	5	55	M	-14	S	5	-39.519
208	318	302	26	OFF	SB	6/11/2004	8:57 AM	8	57	32.03	14	55	D	-13	S	5	-33.382
209	310	0	28	OFF	NB	6/11/2004	8:58 AM	8	58	32.05	1	55	D	-12	S	5	-31.541
210	310	0	28	OFF	SB	6/11/2004	9:05 AM	9	5	32.17	7	55	D	-11	S	5	-38.594
211	203	301	23	OFF	NB	6/11/2004	9:06 AM	9	6	32.18	1	56	D	-10	S	5	-33.239
212	308	309	25	OFF	SB	6/11/2004	9:12 AM	9	12	32.28	6	56	D	-9	S	5	-33.351
213	202	306	22	OFF	NB	6/11/2004	9:22 AM	9	22	32.45	10	56	D	-8	S	5	-32.931
214	301	203	23	OFF	SB	6/11/2004	9:28 AM	9	28	32.55	6	57	D	-7	S	5	-34.122
215	226	313	21	OFF	NB	6/11/2004	9:35 AM	9	35	32.67	7	57	D	-6	S	5	-34.886
216	306	202	25	OFF	SB	6/11/2004	9:41 AM	9	41	32.77	6	58	D	-5	S	5	-30.710
217	312	222	24	OFF	NB	6/11/2004	9:53 AM	9	53	32.97	12	58	D	-4	S	5	-32.550
218	313	226	21	OFF	SB	6/11/2004	9:57 AM	9	57	33.03	4	58	D	-3	S	5	-37.158
219	222	312	24	OFF	SB	6/11/2004	10:15 AM	10	15	33.33	18	58	D	-2	S	5	-36.237
220	308	309	25	OFF	NB	6/11/2004	10:19 AM	10	19	33.40	4	57	D	-1	S	5	-41.950
221	302	318	26	ON	SB	6/11/2004	10:29 AM	10	29	33.57	10	57	D	1	S	5	-42.799
222	301	203	23	ON	NB	6/11/2004	10:34 AM	10	34	33.65	5	57	D	2	S	5	-39.856
223	309	308	25	ON	SB	6/11/2004	10:43 AM	10	43	33.80	9	56	D	3	S	5	-44.885
224	203	301	23	ON	SB	6/11/2004	10:58 AM	10	58	34.05	15	56	D	4	S	5	-44.799
225	306	202	25	ON	NB	6/11/2004	11:04 AM	11	4	34.15	6	56	D	5	S	5	-46.208
226	313	226	21	ON	NB	6/11/2004	11:10 AM	11	10	34.25	6	57	D	6	S	5	-50.855
227	309	308	25	ON	NB	6/11/2004	11:53 AM	11	53	34.97	43	57	D	7	S	5	-50.528
228	318	302	26	ON	SB	6/11/2004	11:57 AM	11	57	35.03	4	58	D	8	S	5	-45.295
229	203	301	23	ON	NB	6/11/2004	12:06 PM	12	6	35.18	9	58	D	9	S	5	-48.351
230	202	306	25	ON	NB	6/11/2004	12:21 PM	12	21	35.43	15	58	D	10	S	5	-47.912
231	301	203	23	ON	SB	6/11/2004	12:28 PM	12	28	35.55	7	58	D	11	S	5	-41.847
232	226	313	21	ON	NB	6/11/2004	12:32 PM	12	32	35.62	4	58	D	12	S	5	-45.717
233	306	202	25	ON	SB	6/11/2004	12:47 PM	12	47	35.87	15	58	M	13	S	5	-39.221
234	312	222	24	ON	NB	6/11/2004	12:49 PM	12	49	35.90	2	58	D	14	S	5	-49.386
235	301	203	23	ON	NB	6/11/2004	1:37 PM	1	37	36.70	48	58	D	15	S	5	-46.087
236	309	308	25	ON	SB	6/11/2004	1:41 PM	1	41	36.77	4	58	D	16	S	5	-42.471
237	306	202	25	ON	NB	6/11/2004	1:48 PM	1	48	36.88	7	59	D	17	S	5	-46.143
238	203	301	23	ON	SB	6/11/2004	1:59 PM	1	59	37.07	11	59	D	18	S	5	-41.989
239	313	226	21	ON	NB	6/11/2004	2:03 PM	2	3	37.13	4	59	D	19	S	5	-50.450
240	202	306	25	ON	SB	6/11/2004	2:11 PM	2	11	37.27	8	59	D	20	S	5	-46.840
241	226	313	21	ON	SB	6/11/2004	2:27 PM	2	27	37.53	16	59	D	21	S	5	-38.385
242	302	318	26	ON	NB	6/11/2004	2:35 PM	2	35	37.67	8	59	D	22	S	5	-49.789
243	302	318	26	ON	SB	6/11/2004	2:41 PM	2	41	37.77	6	59	D	23	S	5	-44.179
244	309	308	25	ON	NB	6/11/2004	2:48 PM	2	48	37.88	7	59	D	24	S	5	-49.265
245	318	302	25	ON	SB	6/11/2004	2:57 PM	2	57	38.03	9	59	D	25	S	5	-40.460
246	310	0	27	ON	NB	6/11/2004	2:58 PM	2	58	38.05	1	59	D	26	S	5	-49.808
247	310	0	27	ON	SB	6/11/2004	3:07 PM	3	7	38.20	9	59	D	27	S	5	-43.811
248	203	301	23	ON	NB	6/11/2004	3:10 PM	3	10	38.25	3	59	D	28	S	5	-50.199
249	306	202	25	ON	SB	6/11/2004	3:41 PM	3	41	38.77	31	58	D	29	S	5	-42.291
250	312	222	24	ON	NB	6/11/2004	3:50 PM	3	50	38.92	9	58	D	30	S	5	-51.008

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
251	225	0	28	ON	NB	6/11/2004	3:57 PM	3	57	39.03	7	58	D	31	S	5	-50.569
252	225	0	28	ON	SB	6/11/2004	4:00 PM	4	0	39.08	3	58	D	32	S	5	-45.791
253	313	226	21	ON	SB	6/11/2004	4:07 PM	4	7	39.20	7	58	D	33	S	5	-41.777
254	318	302	25	ON	NB	6/11/2004	4:08 PM	4	8	39.22	1	58	D	34	S	5	-46.003
255	310	0	27	ON	NB	6/11/2004	4:17 PM	4	17	39.37	9	59	D	35	S	5	-53.617
256	222	312	27	ON	SB	6/11/2004	4:20 PM	4	20	39.42	3	59	D	36	S	5	-43.661
257	302	318	26	ON	SB	6/11/2004	4:28 PM	4	28	39.55	8	59	D	37	S	5	-42.144
258	202	306	25	ON	NB	6/12/2004	7:55 AM	7	55	39.55	0	54	D	38	S	6	-50.712
259	310	237	21	ON	SB	6/12/2004	8:00 AM	8	0	39.63	5	54	D	39	S	6	-41.924
260	222	312	24	ON	NB	6/12/2004	8:09 AM	8	9	39.78	9	54	D	40	S	6	-41.924
261	306	202	25	ON	SB	6/12/2004	8:14 AM	8	14	39.87	5	55	D	41	S	6	-46.488
262	316	206	23	ON	NB	6/12/2004	8:25 AM	8	25	40.05	11	55	D	42	S	6	-54.026
263	203	301	26	ON	NB	6/12/2004	8:39 AM	8	39	40.28	14	55	D	43	S	6	-53.029
264	206	316	23	ON	SB	6/12/2004	8:44 AM	8	44	40.37	5	56	D	44	S	6	-53.247
265	202	306	25	ON	NB	6/12/2004	8:53 AM	8	53	40.52	9	56	D	45	S	6	-48.131
266	301	203	26	ON	SB	6/12/2004	9:02 AM	9	2	40.67	9	56	D	46	S	6	-45.858
267	222	312	24	ON	NB	6/12/2004	9:11 AM	9	11	40.82	9	56	D	47	S	6	-52.862
268	306	202	25	ON	SB	6/12/2004	9:14 AM	9	14	40.87	3	57	D	48	S	6	-48.564
269	316	206	23	ON	NB	6/12/2004	9:23 AM	9	23	41.02	9	57	D	49	S	6	-53.570
270	312	222	24	ON	SB	6/12/2004	9:29 AM	9	29	41.12	6	58	D	50	S	6	-45.788
271	203	301	26	ON	NB	6/12/2004	9:40 AM	9	40	41.30	11	58	D	51	S	6	-50.165
272	206	316	23	ON	SB	6/12/2004	9:44 AM	9	44	41.37	4	59	D	52	S	6	-44.184
273	202	306	25	ON	NB	6/12/2004	9:54 AM	9	54	41.53	10	59	D	53	S	6	-52.213
274	301	203	26	ON	SB	6/12/2004	10:00 AM	10	0	41.63	6	59	D	54	S	6	-41.978
275	222	312	24	ON	NB	6/12/2004	10:15 AM	10	15	41.88	15	60	D	55	S	6	-42.040
276	303	210	21	OFF	NB	6/14/2004	8:02 AM	8	2	41.88	0	57	D	56	S	7	-33.244
277	309	308	22	OFF	NB	6/14/2004	8:25 AM	8	25	42.27	23	57	D	57	S	7	-41.620
278	303	210	21	OFF	SB	6/14/2004	8:28 AM	8	28	42.32	3	57	D	58	S	7	-41.924
279	317	301	26	OFF	NB	6/14/2004	8:36 AM	8	36	42.45	8	57	D	59	S	7	-34.477
280	308	309	22	OFF	SB	6/14/2004	8:39 AM	8	39	42.50	3	56	D	60	S	7	-34.027
281	301	317	26	OFF	SB	6/14/2004	8:57 AM	8	57	42.80	18	56	D	61	S	7	-34.842
282	314	304	24	OFF	NB	6/14/2004	8:59 AM	8	59	42.83	2	56	D	62	S	7	-36.666
283	203	318	23	OFF	NB	6/14/2004	9:09 AM	9	9	43.00	10	57	D	63	S	7	-41.113
284	304	314	24	OFF	SB	6/14/2004	9:12 AM	9	12	43.05	3	57	D	64	S	7	-46.824
285	309	308	22	OFF	SB	6/14/2004	10:14 AM	10	14	44.08	62	58	D	65	S	7	-31.752
286	304	314	22	OFF	NB	6/14/2004	10:27 AM	10	27	44.30	13	59	D	66	S	7	-38.322
287	318	203	23	OFF	NB	6/14/2004	10:03 AM	10	3	43.90	-24	60	D	67	S	7	-35.544
288	314	304	22	OFF	SB	6/14/2004	10:43 AM	10	43	44.57	40	61	D	68	S	7	-32.576
289	302	316	25	OFF	NB	6/14/2004	10:57 AM	10	57	44.80	14	62	D	69	S	7	-47.277
290	203	318	23	OFF	SB	6/14/2004	10:58 AM	10	58	44.82	1	62	D	70	S	7	-47.406
291	210	303	21	OFF	NB	6/14/2004	11:06 AM	11	6	44.95	8	62	D	71	S	7	-30.442
292	316	302	25	OFF	SB	6/14/2004	11:13 AM	11	13	45.07	7	62	D	72	S	7	-32.248
293	309	308	24	OFF	NB	6/14/2004	11:19 AM	11	19	45.17	6	62	D	73	S	7	-36.316
294	317	301	26	OFF	NB	6/14/2004	11:34 AM	11	34	45.42	15	62	D	74	S	7	-40.502
295	308	309	24	OFF	SB	6/14/2004	11:41 AM	11	41	45.53	7	62	D	75	S	7	-35.315
296	314	304	22	OFF	NB	6/14/2004	11:50 AM	11	50	45.68	9	62	D	76	S	7	-41.333
297	301	317	26	OFF	SB	6/14/2004	11:57 AM	11	57	45.80	7	62	D	77	S	7	-36.939
298	203	318	23	OFF	NB	6/14/2004	12:05 PM	12	5	45.93	8	62	D	78	S	7	-31.484
299	302	314	22	OFF	SB	6/14/2004	12:11 PM	12	11	46.03	6	61	D	79	S	7	-39.256
300	316	302	25	OFF	NB	6/14/2004	12:19 PM	12	19	46.17	8	60	D	80	S	7	-39.921

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ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
301	305	315	23	OFF	NB	6/15/2004	7:42 AM	7	42	46.17	0	59	D	-10	AR	8	-40.873
302	303	210	25	OFF	NB	6/15/2004	7:46 AM	7	46	46.23	4	59	D	-9	AR	8	-28.817
303	315	305	23	OFF	SB	6/15/2004	7:54 AM	7	54	46.37	8	58	D	-8	AR	8	-45.135
304	301	317	21	OFF	NB	6/15/2004	7:55 AM	7	55	46.38	1	59	D	-7	AR	8	-31.150
305	226	313	26	OFF	SB	6/15/2004	8:58 AM	8	58	47.43	63	60	D	-6	AR	8	-34.764
306	315	305	23	OFF	NB	6/15/2004	9:05 AM	9	5	47.55	7	60	D	-5	AR	8	-44.487
307	308	309	24	OFF	SB	6/15/2004	9:12 AM	9	12	47.67	7	60	D	-4	AR	8	-33.965
308	210	303	25	OFF	NB	6/15/2004	9:20 AM	9	20	47.80	8	61	D	-3	AR	8	-27.952
309	305	315	23	OFF	SB	6/15/2004	9:28 AM	9	28	47.93	8	61	D	-2	AR	8	-42.247
310	317	301	21	OFF	NB	6/15/2004	9:33 AM	9	33	48.02	5	62	D	-1	AR	8	-32.575
311	303	210	25	ON	SB	6/15/2004	9:41 AM	9	41	48.15	8	62	D	1	AR	8	-33.707
312	222	312	24	ON	NB	6/15/2004	9:49 AM	9	49	48.28	8	63	D	2	AR	8	-48.424
313	301	317	21	ON	SB	6/15/2004	9:57 AM	9	57	48.42	8	63	D	3	AR	8	-38.345
314	226	313	26	ON	NB	6/15/2004	10:04 AM	10	4	48.53	7	63	D	4	AR	8	-39.560
315	312	222	24	ON	SB	6/15/2004	10:14 AM	10	14	48.70	10	64	D	5	AR	8	-45.542
316	308	309	24	ON	NB	6/15/2004	10:18 AM	10	18	48.77	4	64	D	6	AR	8	-41.544
317	313	226	26	ON	SB	6/15/2004	10:29 AM	10	29	48.95	11	65	D	7	AR	8	-43.023
318	305	315	23	ON	NB	6/15/2004	10:33 AM	10	33	49.02	4	65	D	8	AR	8	-50.588
319	309	308	24	ON	SB	6/15/2004	10:43 AM	10	43	49.18	10	66	D	9	AR	8	-43.501
320	303	210	25	ON	NB	6/15/2004	10:52 AM	10	52	49.33	9	66	D	10	AR	8	-51.766
321	315	305	23	ON	SB	6/15/2004	10:58 AM	10	58	49.43	6	66	D	11	AR	8	-50.120
322	301	317	21	ON	NB	6/15/2004	11:06 AM	11	6	49.57	8	67	D	12	AR	8	-54.206
323	317	301	21	ON	SB	6/15/2004	11:28 AM	11	28	49.93	22	67	D	13	AR	8	-39.980
324	313	226	26	ON	NB	6/15/2004	11:34 AM	11	34	50.03	6	68	D	14	AR	8	-50.489
325	309	308	22	ON	NB	6/15/2004	11:49 AM	11	49	50.28	15	68	D	15	AR	8	-40.116
326	226	313	26	ON	SB	6/15/2004	11:56 AM	11	56	50.40	7	69	D	16	AR	8	-39.876
327	305	315	23	ON	SB	6/15/2004	12:27 PM	12	27	50.92	31	70	D	17	AR	8	-51.415
328	317	301	21	ON	NB	6/15/2004	12:33 PM	12	33	51.02	6	71	D	18	AR	8	-49.713
329	303	210	25	ON	SB	6/15/2004	12:47 PM	12	47	51.25	14	72	D	19	AR	8	-41.149
330	222	312	24	ON	NB	6/15/2004	12:48 PM	12	48	51.27	1	73	D	20	AR	8	-50.153
331	301	317	21	ON	SB	6/15/2004	12:57 PM	12	57	51.42	9	73	D	21	AR	8	-39.556
332	226	313	26	ON	NB	6/15/2004	1:02 PM	1	2	51.50	5	73	D	22	AR	8	-50.701
333	308	309	22	ON	NB	6/15/2004	1:19 PM	1	19	51.78	17	73	D	23	AR	8	-51.041
334	313	226	26	ON	SB	6/15/2004	1:27 PM	1	27	51.92	8	73	D	24	AR	8	-48.375
335	305	315	23	ON	NB	6/15/2004	1:33 PM	1	33	52.02	6	74	D	25	AR	8	-50.878
336	309	308	22	ON	SB	6/15/2004	1:41 PM	1	41	52.15	8	74	D	26	AR	8	-49.497
337	303	210	25	ON	NB	6/15/2004	1:51 PM	1	51	52.32	10	75	D	27	AR	8	-52.864
338	315	305	23	ON	SB	6/15/2004	1:56 PM	1	56	52.40	5	75	D	28	AR	8	-48.593
339	301	317	21	ON	NB	6/15/2004	2:05 PM	2	5	52.55	9	75	D	29	AR	8	-52.025
340	317	301	21	ON	NB	6/15/2004	2:19 PM	2	19	52.78	14	75	D	30	AR	8	-52.560
341	317	301	21	ON	SB	6/15/2004	2:27 PM	2	27	52.92	8	75	D	31	AR	8	-49.821
342	313	226	26	ON	NB	6/15/2004	2:31 PM	2	31	52.98	4	75	D	32	AR	8	-53.971
343	222	312	24	ON	SB	6/15/2004	2:42 PM	2	42	53.17	11	76	D	33	AR	8	-48.216
344	309	308	22	ON	NB	6/15/2004	2:47 PM	2	47	53.25	5	76	D	34	AR	8	-50.967
345	226	313	26	ON	SB	6/15/2004	2:56 PM	2	56	53.40	9	76	D	35	AR	8	-47.769
346	306	0	27	ON	NB	6/15/2004	2:58 PM	2	58	53.43	2	76	D	36	AR	8	-50.701
347	306	0	27	ON	SB	6/15/2004	3:07 PM	3	7	53.58	9	76	D	37	AR	8	-47.510
348	315	305	23	ON	NB	6/15/2004	3:09 PM	3	9	53.62	2	76	D	38	AR	8	-51.445
349	317	301	21	ON	NB	6/15/2004	3:34 PM	3	34	54.03	25	76	D	39	AR	8	-50.666
350	303	210	21	ON	SB	6/15/2004	3:41 PM	3	41	54.15	7	76	D	40	AR	8	-51.579

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
351	311	0	0	ON	NB	6/15/2004	3:44 PM	3	44	54.20	3	76	D	41	AR	8	-50.783
352	308	309	22	OFF	SB	6/16/2004	8:08 AM	8	8	54.20	0	63	D	42	AR	9	-34.860
353	301	0	28	OFF	NB	6/16/2004	8:10 AM	8	10	54.23	2	65	D	43	AR	9	-43.479
354	226	313	22	OFF	NB	6/16/2004	8:53 AM	8	53	54.95	43	69	D	44	AR	9	-37.829
355	305	315	26	OFF	SB	6/16/2004	8:57 AM	8	57	55.02	4	69	D	45	AR	9	-38.621
356	304	310	23	OFF	NB	6/16/2004	9:04 AM	9	4	55.13	7	70	D	46	AR	9	-41.605
357	313	226	22	OFF	SB	6/16/2004	9:12 AM	9	12	55.27	8	70	D	47	AR	9	-38.407
358	308	309	25	OFF	NB	6/16/2004	9:21 AM	9	21	55.42	9	71	D	48	AR	9	-44.406
359	310	304	23	OFF	SB	6/16/2004	9:28 AM	9	28	55.53	7	71	D	49	AR	9	-39.025
360	311	317	21	OFF	NB	6/16/2004	9:34 AM	9	34	55.63	6	72	D	50	AR	9	-45.431
361	309	308	25	OFF	SB	6/16/2004	9:42 AM	9	42	55.77	8	72	D	51	AR	9	-41.884
362	210	303	24	OFF	NB	6/16/2004	9:49 AM	9	49	55.88	7	73	D	52	AR	9	-37.423
363	317	311	21	OFF	SB	6/16/2004	9:57 AM	9	57	56.02	8	73	D	53	AR	9	-33.738
364	303	210	24	OFF	SB	6/16/2004	10:16 AM	10	16	56.33	19	74	D	54	AR	9	-32.493
365	313	226	22	OFF	NB	6/16/2004	10:18 AM	10	18	56.37	2	76	D	55	AR	9	-47.309
366	315	305	26	OFF	SB	6/16/2004	10:29 AM	10	29	56.55	11	78	D	56	AR	9	-34.283
367	310	304	23	OFF	NB	6/16/2004	10:34 AM	10	34	56.63	5	79	D	57	AR	9	-44.547
368	308	309	25	OFF	NB	6/16/2004	10:52 AM	10	52	56.93	18	81	D	58	AR	9	-44.704
369	304	310	23	OFF	SB	6/16/2004	10:59 AM	10	59	57.05	7	81	D	59	AR	9	-45.245
370	317	311	21	OFF	NB	6/16/2004	11:06 AM	11	6	57.17	7	82	D	60	AR	9	-41.922
371	308	309	25	OFF	SB	6/16/2004	11:13 AM	11	13	57.28	7	82	D	61	AR	9	-41.491
372	315	305	26	OFF	NB	6/16/2004	11:34 AM	11	34	57.63	21	83	D	62	AR	9	-47.496
373	210	303	24	OFF	SB	6/16/2004	11:42 AM	11	42	57.77	8	83	D	63	AR	9	-41.818
374	226	313	22	OFF	NB	6/16/2004	11:50 AM	11	50	57.90	8	84	D	64	AR	9	-43.040
375	305	315	26	OFF	SB	6/16/2004	11:57 AM	11	57	58.02	7	84	D	65	AR	9	-42.962
376	304	310	23	OFF	NB	6/16/2004	12:10 PM	12	10	58.23	13	84	D	66	AR	9	-45.225
377	313	226	22	OFF	SB	6/16/2004	12:13 PM	12	13	58.28	3	84	D	67	AR	9	-42.330
378	308	309	25	OFF	NB	6/16/2004	12:19 PM	12	19	58.38	6	84	D	68	AR	9	-46.873
379	310	304	23	OFF	SB	6/16/2004	12:27 PM	12	27	58.52	8	84	D	69	AR	9	-43.222
380	311	317	21	OFF	NB	6/16/2004	12:33 PM	12	33	58.62	6	85	D	70	AR	9	-43.331
381	309	308	25	OFF	SB	6/16/2004	12:43 PM	12	43	58.78	10	85	D	71	AR	9	-50.998
382	210	303	24	OFF	NB	6/16/2004	12:47 PM	12	47	58.85	4	85	D	72	AR	9	-44.045
383	317	311	21	OFF	SB	6/16/2004	12:56 PM	12	56	59.00	9	85	D	73	AR	9	-42.062
384	305	315	26	OFF	NB	6/16/2004	1:04 PM	1	4	59.13	8	85	D	74	AR	9	-49.829
385	303	210	24	OFF	SB	6/16/2004	1:10 PM	1	10	59.23	6	85	D	75	AR	9	-47.828
386	313	226	22	OFF	NB	6/16/2004	1:20 PM	1	20	59.40	10	86	D	76	AR	9	-51.171
387	315	305	26	OFF	SB	6/16/2004	1:26 PM	1	26	59.50	6	86	D	77	AR	9	-48.663
388	310	304	23	OFF	NB	6/16/2004	1:33 PM	1	33	59.62	7	87	D	78	AR	9	-50.097
389	226	313	22	OFF	SB	6/16/2004	1:41 PM	1	41	59.75	8	87	D	79	AR	9	-51.185
390	317	311	21	OFF	NB	6/16/2004	2:05 PM	2	5	60.15	24	87	D	80	AR	9	-52.103
391	303	210	24	OFF	NB	6/16/2004	2:18 PM	2	18	60.37	13	87	D	81	AR	9	-43.511
392	0	216	0	OFF	NB	6/17/2004	7:42 AM	7	42	60.37	0	68	D	-12	B	10	-43.337
393	317	311	25	OFF	SB	6/17/2004	8:08 AM	8	8	60.80	26	69	D	-11	B	10	-38.780
394	316	0	0	OFF	NB	6/17/2004	8:10 AM	8	10	60.83	2	69	D	-10	B	10	-28.979
395	316	0	0	OFF	SB	6/17/2004	8:17 AM	8	17	60.95	7	70	D	-9	B	10	-40.621
396	110	248	24	OFF	NB	6/17/2004	8:22 AM	8	22	61.03	5	70	D	-8	B	10	-35.576
397	226	313	21	OFF	SB	6/17/2004	8:28 AM	8	28	61.13	6	71	D	-7	B	10	-37.785
398	302	222	24	OFF	NB	6/17/2004	8:34 AM	8	34	61.23	6	71	D	-6	B	10	-36.367
399	248	110	24	OFF	SB	6/17/2004	8:41 AM	8	41	61.35	7	72	D	-5	B	10	-36.287
400	304	310	22	OFF	NB	6/17/2004	8:52 AM	8	52	61.53	11	73	D	-4	B	10	-35.138

ROW	CAR_1	CAR_2	CON#	ON - OFF	NB - SB	DATE	TIME	HOUR	MINS	CUM_HRS	DEL_MINS	DEGS F	RAIN wmd	PASS #	LUBE	DAY #	SPCAVG RLTV-DB
401	222	302	24	OFF	SB	6/17/2004	8:58 AM	8	58	61.63	6	73	D	-3	B	10	-44.402
402	216	219	23	OFF	NB	6/17/2004	9:05 AM	9	5	61.75	7	74	D	-2	B	10	-43.105
403	317	311	25	OFF	NB	6/17/2004	9:22 AM	9	22	62.03	17	75	D	-1	B	10	-40.013
404	219	216	23	ON	SB	6/17/2004	9:28 AM	9	28	62.13	6	76	D	1	B	10	-45.047
405	226	313	21	ON	NB	6/17/2004	9:32 AM	9	32	62.20	4	77	D	2	B	10	-36.224
406	311	317	25	ON	SB	6/17/2004	9:41 AM	9	41	62.35	9	78	D	3	B	10	-37.428
407	248	110	24	ON	NB	6/17/2004	9:49 AM	9	49	62.48	8	78	D	4	B	10	-43.815
408	313	226	21	ON	SB	6/17/2004	9:56 AM	9	56	62.60	7	79	D	5	B	10	-42.733
409	222	302	24	ON	NB	6/17/2004	10:03 AM	10	3	62.72	7	80	D	6	B	10	-51.734
410	110	248	24	ON	SB	6/17/2004	10:14 AM	10	14	62.90	11	81	D	7	B	10	-39.653
411	310	304	22	ON	NB	6/17/2004	10:18 AM	10	18	62.97	4	82	D	8	B	10	-52.785
412	302	222	24	ON	SB	6/17/2004	10:29 AM	10	29	63.15	11	83	D	9	B	10	-43.974
413	219	216	23	ON	NB	6/17/2004	10:34 AM	10	34	63.23	5	84	D	10	B	10	-51.917
414	304	310	22	ON	SB	6/17/2004	10:43 AM	10	43	63.38	9	84	D	11	B	10	-42.408
415	311	317	25	ON	NB	6/17/2004	10:53 AM	10	53	63.55	10	85	D	12	B	10	-50.901
416	216	219	23	ON	SB	6/17/2004	10:58 AM	10	58	63.63	5	85	D	13	B	10	-48.350
417	313	226	21	ON	NB	6/17/2004	11:05 AM	11	5	63.75	7	85	D	14	B	10	-51.764
418	317	311	25	ON	SB	6/17/2004	11:12 AM	11	12	63.87	7	86	D	15	B	10	-40.794
419	110	248	24	ON	NB	6/17/2004	11:20 AM	11	20	64.00	8	86	D	16	B	10	-52.156
420	302	222	22	ON	NB	6/17/2004	11:35 AM	11	35	64.25	15	87	D	17	B	10	-51.737
421	248	110	24	ON	SB	6/17/2004	11:41 AM	11	41	64.35	6	88	D	18	B	10	-41.063
422	304	310	22	ON	NB	6/17/2004	11:50 AM	11	50	64.50	9	88	D	19	B	10	-52.399
423	222	302	22	ON	SB	6/17/2004	11:57 AM	11	57	64.62	7	89	D	20	B	10	-47.179
424	216	219	23	ON	NB	6/17/2004	12:06 PM	12	6	64.77	9	89	D	21	B	10	-51.331
425	310	304	22	ON	SB	6/17/2004	12:12 PM	12	12	64.87	6	89	D	22	B	10	-44.457
426	317	311	25	ON	NB	6/17/2004	12:22 PM	12	22	65.03	10	89	D	23	B	10	-52.496
427	226	313	21	ON	NB	6/17/2004	12:32 PM	12	32	65.20	10	90	D	24	B	10	-52.324
428	248	110	24	ON	NB	6/17/2004	12:48 PM	12	48	65.47	16	90	D	25	B	10	-51.447
429	313	226	21	ON	SB	6/17/2004	12:57 PM	12	57	65.62	9	90	D	26	B	10	-51.714
430	110	248	24	ON	SB	6/17/2004	1:11 PM	1	11	65.85	14	90	D	27	B	10	-49.738
431	310	304	22	ON	NB	6/17/2004	1:20 PM	1	20	66.00	9	90	D	28	B	10	-51.884
432	302	222	22	ON	SB	6/17/2004	1:26 PM	1	26	66.10	6	90	D	29	B	10	-52.031
433	219	216	23	ON	NB	6/17/2004	1:33 PM	1	33	66.22	7	90	D	30	B	10	-49.644
434	311	317	25	ON	NB	6/17/2004	1:49 PM	1	49	66.48	16	90	D	31	B	10	-51.835

ANNEX D—SOUND LEVEL PLOTS BY LUBRICANT & DIRECTION OF TRAVEL

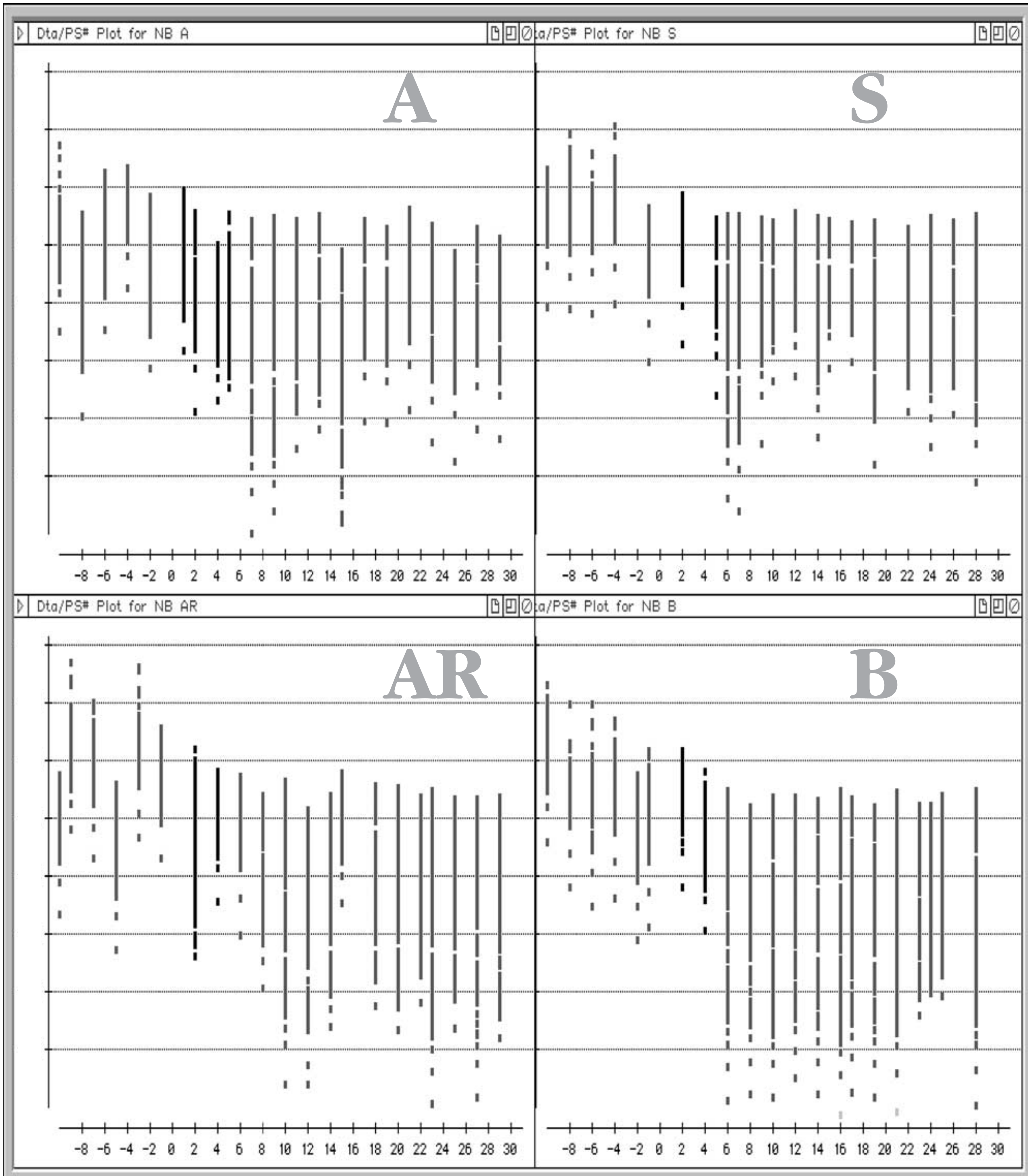


Figure 21—Sound levels from the four tested lubricants showing only northbound data.

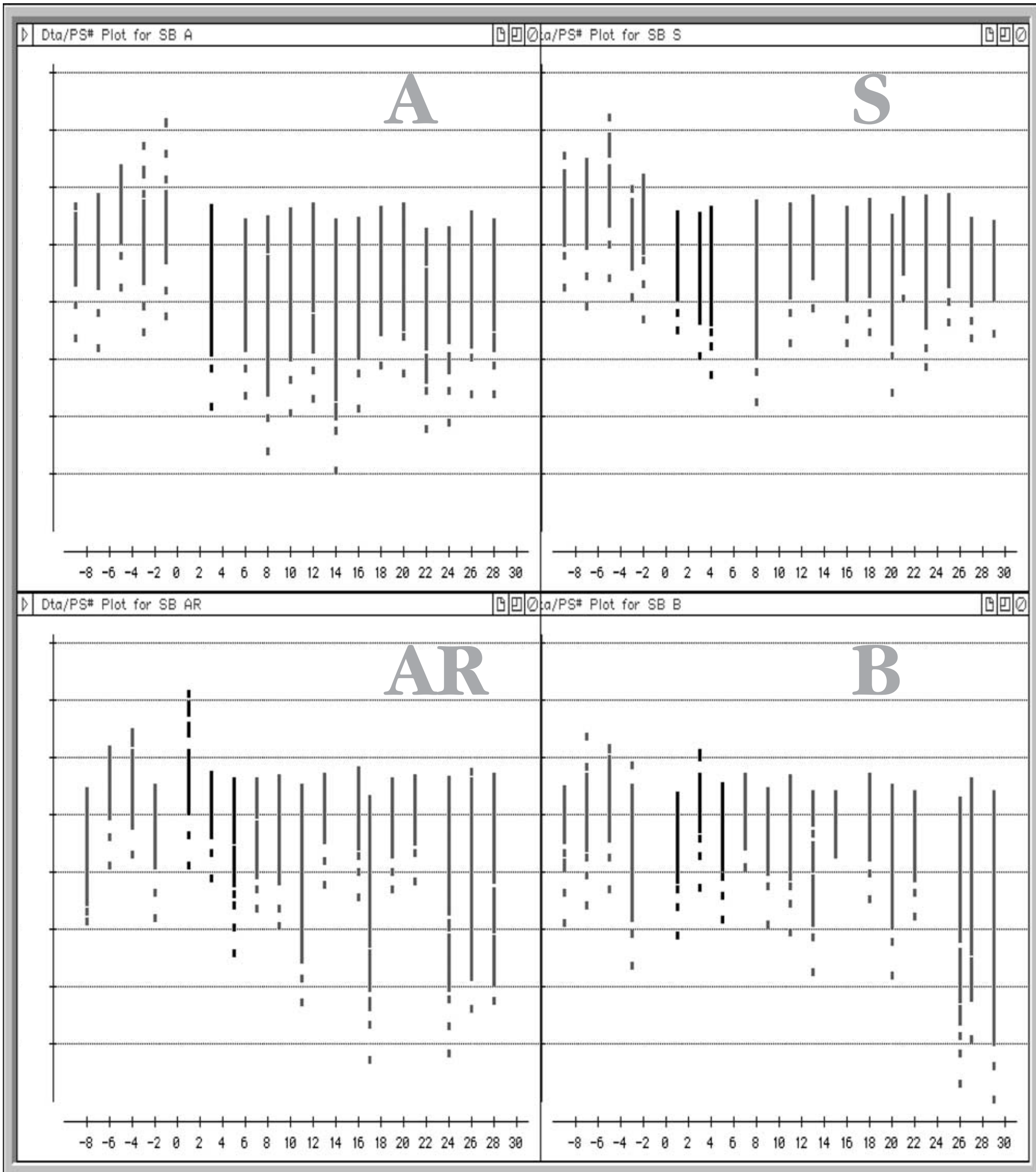


Figure 22—Sound levels from the four tested lubricants showing only the southbound data.

Table 3—Summary values of lube & direction displays shown in Annex D.

LUBE	DIRECTION	DIFFERENCE DRY-LUBED	RANGE PASS# >>	MEAN DRY -10…-1	MEAN_TRANS 1…6	MEAN LUBED 7…29
A	NB	9		-41	-46	-50
AR	NB	16		-34	-43	-50
B	NB	15		-37	-44	-52
S	NB	14		-35	-46	-49
	NB AVG	14		-36	-45	-50
A	SB	8		-38	-46	-47
AR	SB	6		-39	-39	-45
B	SB	6		-40	-42	-46
S	SB	8		-34	-44	-42
	SB AVG	7		-38	-44	-45

The above table contains measured decibel voltages (and some decibel sound level reductions attained by the tested lubricants in column 3) observed in the three major operating conditions depicted by the blocks of Figures 21 and 22. The three modes of operation include Dry Rail (5th column), Transition from Dry to Lubed (shaded black column 6), and Fully Lubricated conditions (last column). Higher positive values of column 3 indicate greater reductions in the sounds observed. Negative values in columns 5, 6, and 7 indicate the opposite response (i.e., the –34 decibel level is noisier than the –50 decibel observed level).

Also note: Data shown contain all frequency bands in the collected spectra taken under the operating conditions listed. If only frequencies in the 1,000-hertz range were displayed, the sound level reduction would not be as great, but if selective frequencies in the 5,000-hertz-and-above range were summarized, then even greater reductions (say 20 decibels) in sound level would be found. For a summary of how sound level depends on frequency, see Figure 3 in this appendix.

APPENDIX B

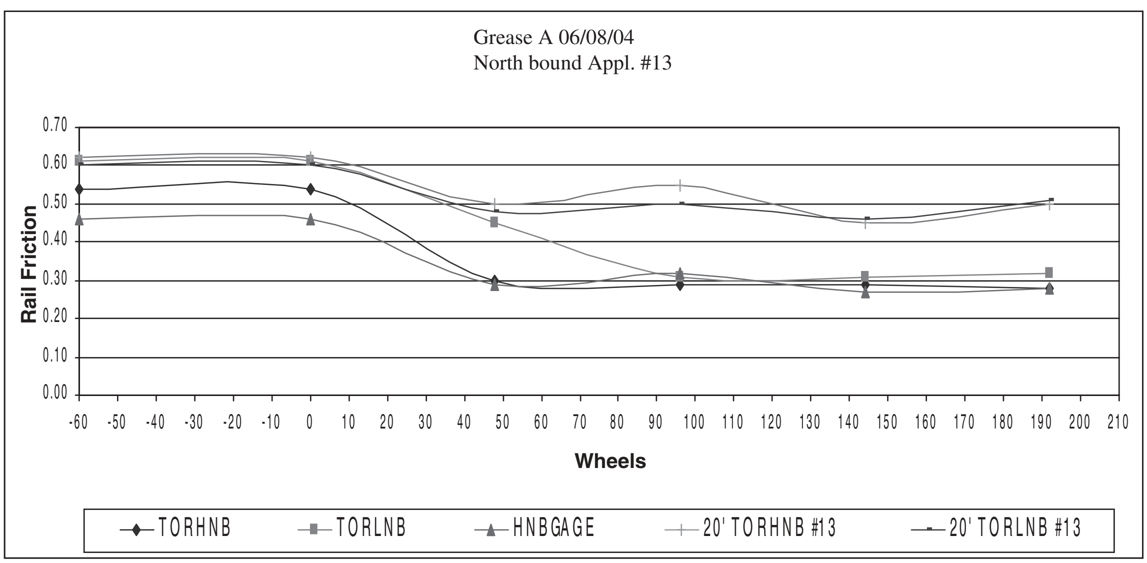
SUMMARY OF RAIL FRICTION DATA

Rail friction data were obtained with a tribometer. The lubricant applicators were turned off a few days before testing to establish a dry rail baseline. Rail friction readings were taken approximately every hour, or after four train passes.

The graphs represent the rail friction readings versus the number of wheels per train. The negative values for the wheels merely represent the time prior to turning on the lubricant applicators.

Graph Labels	Definitions
TORHNB	Top of high rail, northbound tracks
TORLNB	Top of low rail, northbound tracks
HNBGAGE	Gage corner of high rail, northbound track
20'TORHNB#1	3Top of high rail, northbound, 20 feet before Applicator #13
20'TORLNB#13	Top of low rail, northbound, 20 feet before Applicator #13
TORHSB	Top of high rail, southbound tracks
TORLSB	Top of low rail, southbound tracks
HSBGAGE	Gage corner of high rail, southbound track

The weather affected the tribometer readings. Moisture can allow lower rail friction. In addition, higher temperatures will allow residual grease to flow onto the wheel path, thus lowering rail friction.



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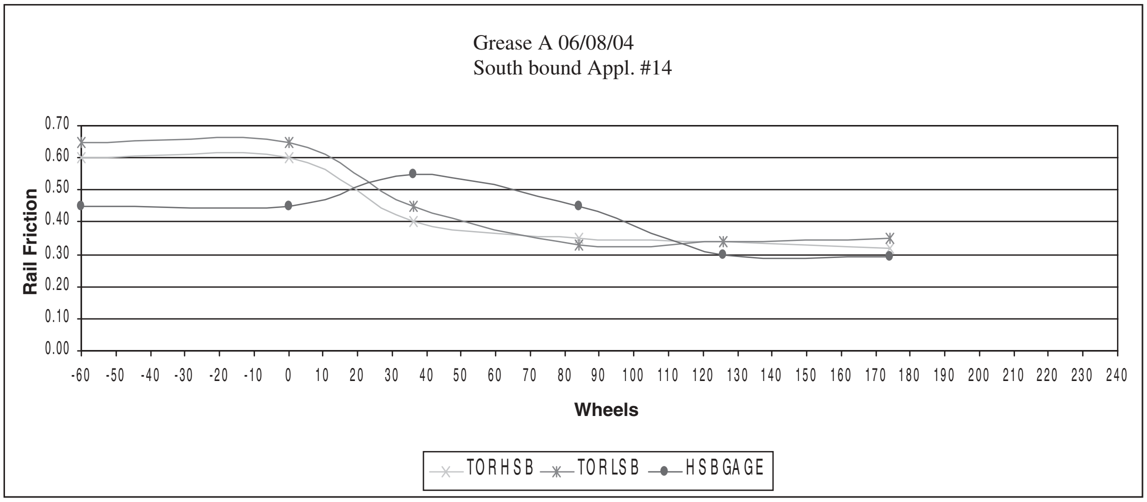
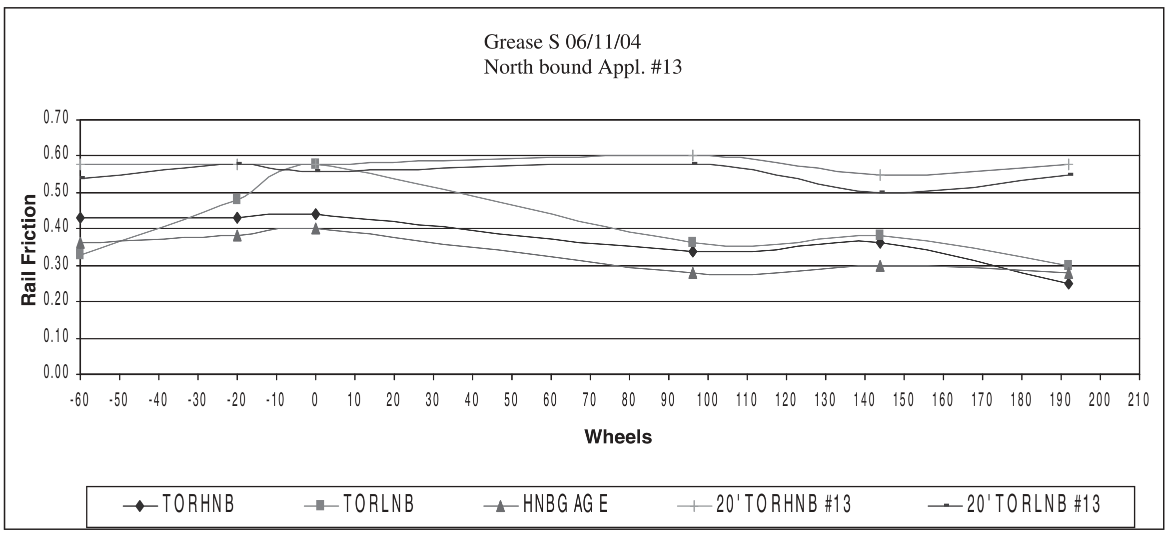
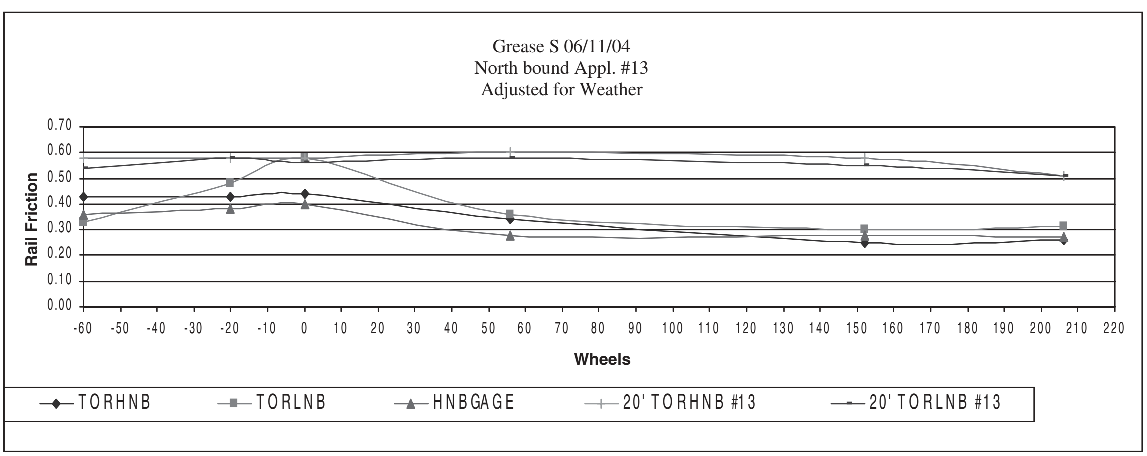
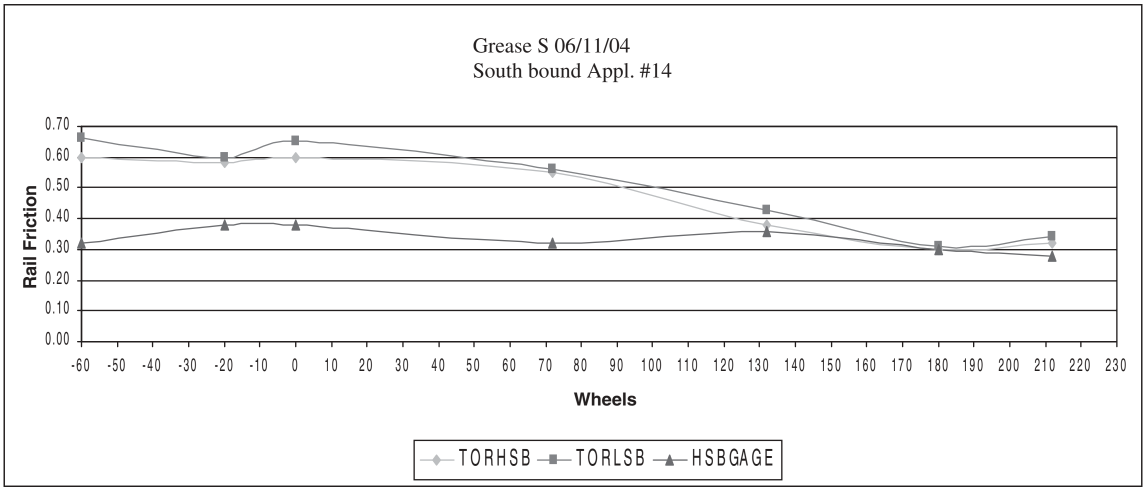


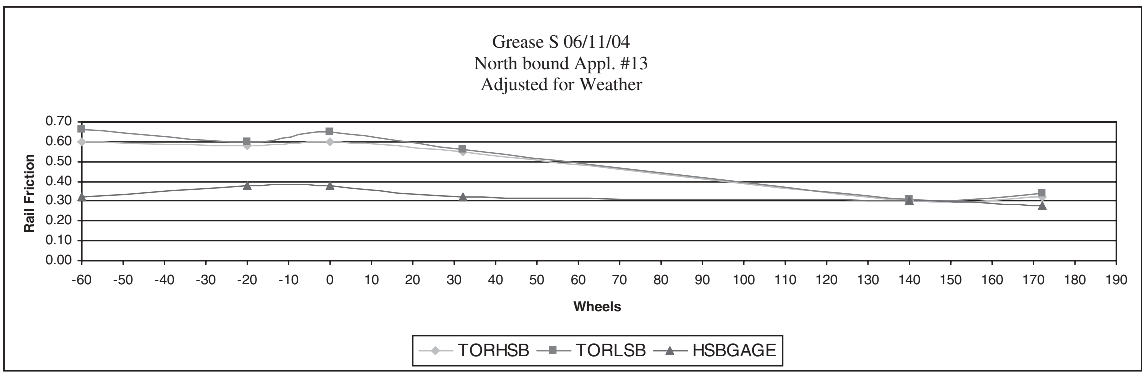
The following two plots for Grease S are based on raw data; however, rain interfered during some of the application period.



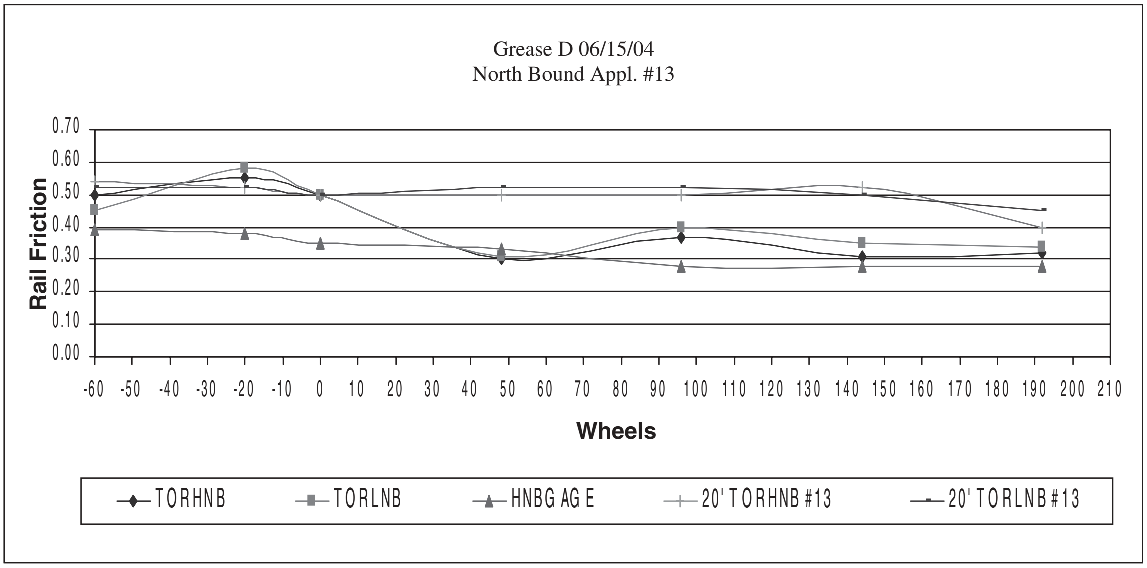


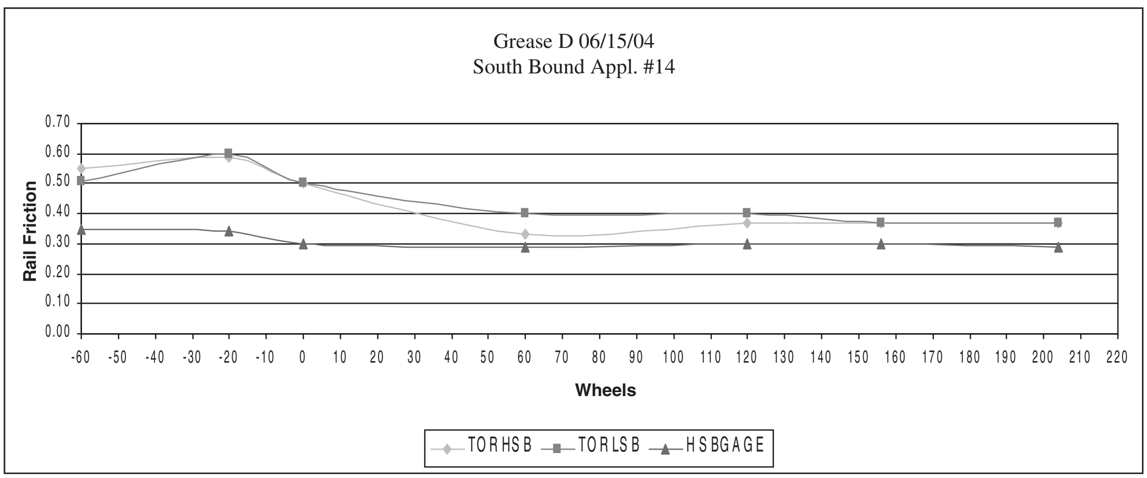
Grease S data adjusted for weather conditions are as follows:

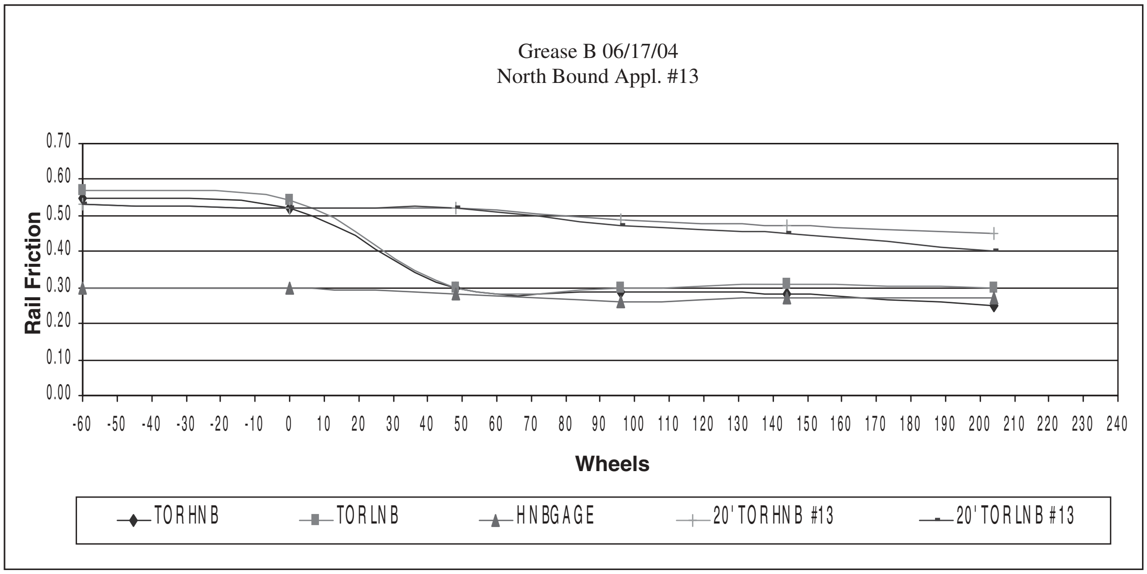


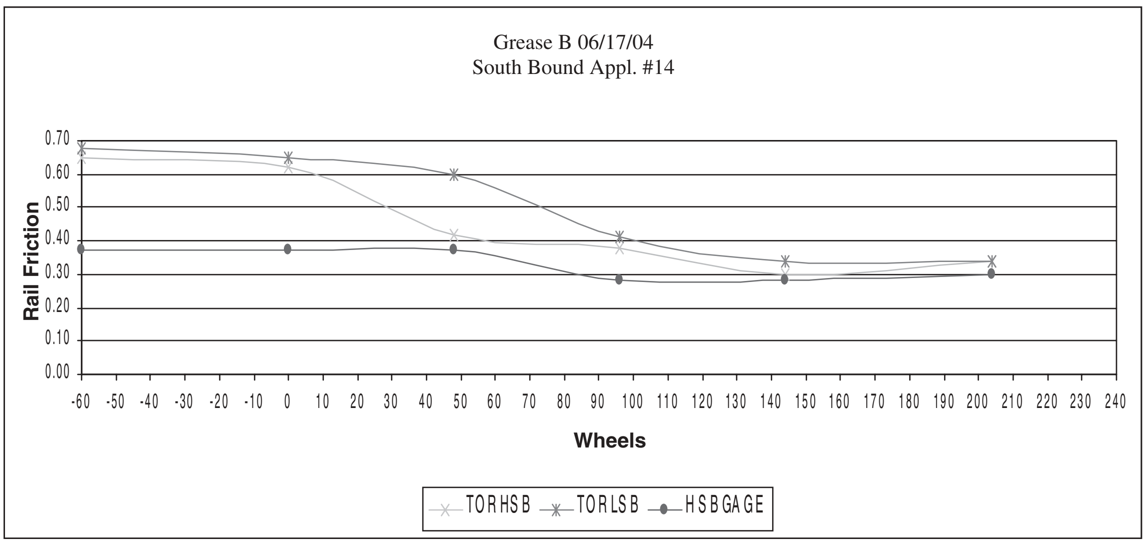


Intermittent rainfall occurred during June 11, 2004, testing; thus, an adjustment to the data was applied. Time duration of the rain and train passes were taken into account, and the data were re-plotted. The steady state values were not affected. Approximately 40 axle passes were subtracted from the original data.


Grease D 06/15/04
North Bound Appl. #13
Rail Friction
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Wheels
TORHNB
TORLNB
HNBGAGE
20' TORHNB #13
20' TORLNB #13


Grease D 06/15/04
South Bound Appl. #14
Rail Friction
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
Wheels
TORHSB
TORLSB
HSBGAGE


Grease B 06/17/04
North Bound Appl. #13
Rail Friction
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240
Wheels
TORHNB
TORLNB
HNBGAGE
20' TORHNB #13
20' TORLNB #13


Grease B 06/17/04
South Bound Appl. #14
Rail Friction
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240
Wheels
TORHSB
TORLSB
HSBGAGE

APPENDIX C

PORTLAND TRIMET TRAIN AND APPLICATOR ADJUSTMENT RUN LOG, JUNE 7–17, 2004

								Tribo						
60704	Time	Consist	Lead	Trail	Direction	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	1000					0.36	0.55	0.30	0.60	0.60	0.32			
	1200					0.36	0.55	0.30	0.60	0.60	0.32			
	1212	22	222	312	SB									
	1218	25	302	310	NB									
	1228	23	212	233	SB									
	1232	21	306	318	NB									
	1243	25	310	302	SB									
	1249	24	234	317	NB									
	1256	21	318	306	SB									
	1306	26	307	250	NB									
	1311	24	317	234	SB									
	1318	22	222	312	NB									
	1328	26	250	307	SB									
	1334	23	212	233	NB									
	1341	24	312	222	SB									
	1349	25	310	302	NB									
	1356	23	233	212	SB									
	1404	21	318	306	NB	0.36	0.55	0.28	0.53	0.50	0.32			
	1413	25	302	310	SB									
	1419	24	317	234	NB									
	1427	21	306	318	SB									
	1431	26	250	307	NB									
	1442	24	234	317	SB									
	1448	22	312	222	NB									
	1451	26	307	250	SB									
	1503	27	301	SC	NB									
	1508	27	301	SC	SB									NO DATA
	1509	23	233	212	NB									
	1518	22	222	312	SB									NO DATA
	1523	25	302	310	NB									
	1532	23	212	233	SB									NO DATA
	1533	21	306	318	NB									NO DATA
	1541	25	310	302	SB									
	1545	28	305	SC	NB									
	1551	24	234	317	NB									
	1557	28	305	SC	SB									
	1603	26	307	250	NB	0.35	0.44	0.34	0.46	0.47	0.36	0.43	0.47	STARTED SPIRINKLING
	1618	27	301	SC	NB									
	1620	24	317	234	SB									TORHNB DRY / DUE TO TREE COVER
	1628	26	250	307	SB									
	1629	22	222	312	NB									STOPPED RAINING
	1642	27	301	SC	SB									
	1644	23	212	233	NB									
	1648	22	312	222	SB									
	1652	25	310	302	NB									
	1658	23	233	212	SB	0.57	0.47	0.30	0.60	0.63	0.35	0.59	0.60	RAIL DRY BOTH DIRECTIONS
	1706	28	305	SC	NB									
	1710	25	302	310	SB									
	1716	21	318	306	NB									STARTED RAINING / DONE FOR THE DAY
	1718	28	305	SC	SB									

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								Tribo						COOL & CLOUDY / LIGHT DRIZZLE IN AM
6/8/2004	Date-time	Consist	Lead	Trail	Direction	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	1016	24	306	318	SB									RAIL DRYING OUT
	1018	22	226	313	NB									
	1029	26	234	317	SB									
	1033	23	204	315	NB									
	1043	22	313	226	SB									
	1051	25	222	312	NB									
	1100	23	315	204	SB	0.54	0.61	0.46	0.60	0.65	0.45	0.62	0.60	RAIL DRY
	1107	21	301	203	NB									
	1112	25	312	222	SB									
	1122	24	306	318	NB									CAR # 318 SEEMS TO HAVE A FLAT SPOT ON WHEEL
	1128	21	203	301	SB									
	1133	26	234	317	NB									
	1142	24	318	306	SB									
	1151	22	313	226	NB									
	1158	26	317	234	SB									
Wheels	1200					0.54	0.61	0.46	0.60	0.65	0.45	0.62	0.60	Grease "A" Applicator #13 & #14 turned on
12	1205	23	315	204	NB									
	1213	22	226	313	SB									
12	1219	25	312	222	NB									
	1229	23	204	315	SB									
12	1236	21	203	301	NB									
	1242	25	222	312	SB									
12	1250	24	318	306	NB	0.30	0.45	0.29	0.40	0.45	0.55	0.50	0.48	
	1257	21	301	203	SB									
12	1304	26	317	234	NB									
	1312	24	306	318	SB									
12	1321	22	222	313	NB									
	1327	26	234	317	SB									
12	1338	23	315	SC	NB									
	1342	22	313	226	SB									
12	1354	25	222	312	NB	0.29	0.31	0.32	0.35	0.33	0.45	0.55	0.50	
	1356	23	315	SC	SB									
12	1405	21	301	303	NB									
	1412	25	312	222	SB									
12	1419	24	306	318	NB									
	1428	21	203	301	SB									
12	1433	26	234	317	NB									
	1442	24	318	306	SB									
12	1450	22	313	226	NB	0.29	0.31	0.27	0.34	0.34	0.30	0.45	0.46	
	1454	26	317	234	SB									
12	1500	27	305	SC	NB									
	1510	27	305	SC	SB									
12	1511	23	315	SC	NB									

6/9/2004									Tribo						COOL & CLOUDY / LIGHT DRIZZLE IN AM
Date-time	Consist	Lead	Trail	Direction	NB Wheel:	SB Wheel:	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
740							0.36	0.32	0.33	0.59	0.60	0.50	0.55	0.53	Rain overnight, rail wet in am.
732	27	317	SC	SB		6									Calibrated microphones
743	23			NB	12										NO DATA
747	25	302	310	NB											NO DATA
754	23	309	308	SB											NO DATA
755	21	252	311	NB											DATA
808	25	310	302	SB											
810	28	318	SC	NB											NO DATA
818	28	318	SC	SB											
826	24	313	226	NB											
828	21	311	252	SB											
835	26	222	312	NB											
841	24	226	313	SB											
54	22	203	301	NB											
858	26	312	222	SB											
907	23	309	308	NB											
912	22	301	203	SB											#13 Applicator has 273 activations
921	25	310	302	NB											Light mist starting.....
928	23	308	309	SB			0.23	0.32	0.32	0.57	0.58	0.35	0.50	0.45	
937	21	311	252	NB											
942	25	302	310	SB											
948	24	226	313	NB											
958	21	252	311	SB											
1004	26	312	222	NB											
1016	24	313	226	SB											
1019	22	301	203	NB											
1030	26	222	312	SB											NO DATA
1035	23	308	309	NB											NO DATA
1121	24	313	226	NB			0.37	0.33	0.45	0.45	0.51	0.36	0.48	0.49	
1129				SB											MISSED CAR #S
1125				NB											MISSED CAR #S
1143	24	226	313	SB											raining, shutting down for luch & weather
1150	22	203	301	NB											Counter #13 @308 @ 1210 /shutdown for lunch
1343	22	203	301	SB			0.29	0.33	0.30	0.37	0.44	0.33	0.56	0.50	NO DATA / Counter #13 @ 330
1349	25	302	310	NB											NO DATA / Counter #14 @438
1356	23	309	308	SB											1100 feet from #14 to mic's
1404	21	252	311	NB											133 feet from #13 to mic's
1413	25	310	302	NB											
1423	24	301	203	NB											
1427	21	311	252	SB											
1442	24	203	301	SB											
1444	26	222	312	NB			0.28	0.28	0.30	0.31	0.38	0.40	0.50	0.48	
1456	26	312	222	SB											
1458	22	226	313	NB											
1504	27	318	SC	NB			0.27	0.35							applicator #13 turned off, counter @348
1508	27	318	SC	SB											
1509	23	309	308	NB											applicator #14 turned off, counter @462
1518	22	313	226	SB											
1532	23	308	309	SB											
1534	25	310	302	NB											
1543	21	311	252	NB											
1544	25	302	310	SB											
1546	28	306	SC	NB											
1557	28	306	SC	SB											
1603	24	203	301	NB											
1607	21	252	311	SB			0.37	0.34	0.30	0.36	0.40	0.30	0.55	0.50	
1608	26	312	222	NB											
1619	24	301	203	SB											
1620	27	318	SC	NB											
1627	26	222	312	SB											
1628	22	313	226	NB											
1650	27	318	SC	SB											
1652	23	308	309	NB											
1656	22	226	313	SB											
1657	25	302	310	NB											
1702	23	309	308	SB			0.33	0.35	0.29	0.35	0.45	0.28	0.55	0.52	
1707	28	306	SC	NB											
1709	25	310	302	SB											
1717	21	252	311	NB											

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								Tribo							
6/10/2004	Time	Consist	Lead	Trail	Direction	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHN	20' TORLN	COMMENTS	
														Rained overnight, rail dry, applicator not oozing	
	730													Setup Mics and calibrate	
	840					0.40	0.35	0.36	0.60	0.68	0.35	0.55	0.50		
	850													Rich Smith taking data, left to get Reiff from Hotel	
	912	21	212	311	SB										
	921	25	226	313	NB										
	925													Raining hard, stopped data, took Rieff to airport	
	1030													returned to site, rail dry, cloudy some sprinkles	
	1100													dry , overcast, cool	
	1115													rail sounds dry nb & sb	
	1138					0.43	0.43							tribo on nb tor / there seems to be some	
	1300					0.43	0.33	0.36	0.60	0.66	0.32	0.58	0.54	broke for lunch, waiting out some dark clouds	
	1310	24	312	222	SB									No audio data	
	1320	22	212	311	NB									No audio data	
	1327	26	203	301	SB									Audio data	
	1333	23	240	103	NB										
	1342	22	311	212	SB										
	1351	25	313	226	NB										
	1357	23	103	240	SB									No audio data	
	1405	21	309	308	NB										
	1412	25	226	313	SB										
	1420	24	312	222	NB										
	1422	21	308	309	SB									No audio data	
	1430					0.43	0.33								
	1440	26	203	301	NB										
	1443	24	222	312	SB										
	1447	22	311	212	NB										
	1456	26	301	203	SB										
	1500	27	310	SC	NB										
	1508	27	310	SC	SB										
	1511	23	103	240	NB										
	1518	22	212	311	SB										
	1522	25	226	313	NB										
	1532	23	240	103	SB										
	1534	21	308	309	NB										

6/11/2004	Time	Consist	Lead	Trail	Direction	SB Wheels	NB Wheels	TORHNB	TORLNB	Tribo HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	700															Setup/ calibration/ NB & SB sound real dry
	730					-20	-20	0.43	0.48	0.38	0.58	0. 6	0.38	0. 58	0.58	
	800	22	306	202	NB											
	812	22	202	306	SB											
	814	25	309	308	NB											
	828	21	226	313	SB											Started to sprinkle real light
	829	24	222	312	NB											
	839	24	312	222	SB											
	844	26	302	318	NB											Kinda spitting off and on
	857	26	318	302	SB											
	859	28	310	SC	NB											
	905	28	310	SC	SB											
	906	23	203	301	NB											light sprinkle
	913	25	308	309	SB											
	923	22	202	306	NB											
	929	23	301	203	SB											
	935	21	226	313	NB											
	942	22	306	202	SB											
	953	24	312	222	NB											
	1000					0	0	0.44	0.58	0.4	0.6	0.65	0.38	0.58	0.56	
	1006	26	318	302	NB											
	1020															Turned #14 SB Applicator with Grease S 5 pre-counts
	1028															Turned #13 NB Applicator with Grease S 5 pre-counts
	1030	26	302	318	SB	12										
	1034	23	301	203	NB		12									
	1043	25	309	308	NB		24									
	1059	23	203	301	SB	24										
	1105	22	306	202	NB		36									
	1110	21	313	226	NB		48									
	1116	22	202	306	SB	36										Rained for 5 min. covered mics / no data
	1128	21	226	313	SB	48										Stopped light drizzle , rail drying up again / no data
	1130	24	222	312	NB		60									
	1134	26	302	318	NB		72									
	1143	24	312	222	SB	60										
	1154	25	309	308	NB		84									SB dry, NB spottty
	1157	26	318	302	SB	72										
	1206	23	203	301	NB		96									
	1215					72	96	0.34	0.36	0.28	0.55	0.56	0.32	0.6	0.58	21 total counts #13 (16 delta @ 5 trains)
	1218	x	x	x	SB	84										
	1221	25	202	306	NB		108									
	1228	23	301	203	SB	96										
	1233	21	226	313	NB		120									

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6/12/2004	Time	Consist	Lead	Trail	Direction	TORHNB	TORLNB	Tribo HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	730													Setup/ calibration / #14 310 cnts@0730 / #13 186 cnts@0738
	740				NB									Cool overcast, R. Smith took pics of rail.... Grease formed over wear path..
	746	22	313	226	SB									
	756	25	202	306	NB									
	800	21	310	237	SB									
	809	24	222	312	NB									
	814	25	306	202	SB									
	826	23	316	206	NB									
	830					0.33	0.35	0.26	0.35	0.37	0.28	0.5	0.5	
	835				SB									
	840	26	203	301	NB									
	844	23	206	316	SB									
	853	25	202	306	NB									
	902	26	301	203	SB									
	912	24	222	312	NB									
	915	25	306	202	SB									
	924	23	316	206	NB									
	929	24	312	222	SB									
	944	26	203	301	NB									
	945	23	206	316	SB	0.3	0.31	0.29	0.33	0.39	0.29	0.52	0.5	
	954	25	202	306	NB									
	1000	26	301	203	SB									
	1009													Turned #13 applicator off..... 209 counts, (204 minus the 5 pre-pumps)
	1020													Turned #14 applicator off..... 358 counts, (353 minus the 5 pre-pumps)
	1100													no data

6/14/2004	Time	Consist	Lead	Trail	Direction	TORHNB	TORLNB	Tribo HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	715													Setup / calibration
	809		204	SC	SB									
	810	25	316	202	NB									
	815					0.5	0.45	0.39	0.55	0.51	0.35	0.54	0.52	
	825	22	309	308	NB									
	828	21	303		SB									
	837	26	317	301	NB									
	840	22	308	309	SB									
	857	26	301	317	SB									
	900	24	314	304	NB									
	909	23	203	318	NB									Starting to mist
	913	24	304	314	SB									
	915													Raining, covered mic's, no data
	929	23	318	203	SB									No data
	933	21	303	210	NB									
	942	25	302	316	SB									
	948	22	308	309	NB									
	957	21	210	303	SB									
	1007	26	301	317	NB									Uncovered mic's
	1017	24	309	308	SB									Data
	1027	22	304	314	NB									No B&K Data
	1029	26	317	301	SB									No B&K Data
	1033	23	318	203	NB									Data
	1043	22	314	304	SB									
	1052	25	302	316	NB									
	1058	23	203	318	SB									
														Shut down for the day, the next grease is in Portland but not delivered to tri met
														Going to resume in the am with a few dry runs then lube up.

										Tribo						
	Date-time	Consist	Lead	Trail	Direction	SB Wheel:	NB Wheel:	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
6/15/2004	700					-60	-60	0.5	0.45	0.39	0.55	0.51	0.35	0.54	0.52	
	730															Setup / Calibrations
	755	23	315	305	SB											
	756	21	301	317	NB											
	809	25	210	303	SB											
	811	28	318	SC	NB											
	819	28	318	SC	SB											
	820					-20	-20	0.55	0.58	0.38	0.59	0.6	0.34	0.52	0.52	dry data / cool, clear, purging grease lines
	823				NB											
	836	26	313	226	NB											
	840	24	222	312	SB											
	934	21	317	301	NB											
	941	25	303	210	SB											
	945					0										Applicator #14 turned on, counter zeroed
	949	24	222	312	NB											
	958	21	301	317	SB	12										
	1005	26	226	313	NB											
	1009						0									Applicator #13 turned on, counter zeroed
	1014	24	312	222	SB	24										
	1017	22	308	309	NB		12									
	1030	26	313	226	SB	36										
	1034	23	305	315	NB		24									
	1043	22	309	308	SB	48										
	1053	25	303	210	NB		36									
	1059	23	315	305	SB	60										
	1106	21	301	317	NB		48									
	1110					60	48	0.3	0.31	0.33	0.33	0.4	0.29	0.5	0.52	
	1112	25	210	303	SB	72										No B&K Data
	1121	24	312	222	NB		60									No B&K Data
	1128	21	317	301	SB	84										
	1132	26	313	226	NB		72									
	1142	24	222	312	SB	96										No B&K Data
	1150	22	309	308	NB		84									
	1157	26	226	313	SB	108										
	1207	23	315	305	NB		96									
	1211	22	308	309	SB	120										
	1212					120	96	0.37	0.4	0.28	0.37	0.4	0.3	0.5	0.52	
	1222	x	x	x	NB		108									
	1227	23	305	315	SB	132										
	1233	21	317	301	NB		120									
	1242	25	303	210	SB	144										
	1250	24	222	312	NB		132									
	1257	21	301	317	SB	156										
	1302	26	226	313	NB		144									
	1310					156	144	0.31	0.35	0.28	0.37	0.37	0.3	0.52	0.5	
	1312	x	x	x	SB	168										
	1320	22	308	309	NB		156									
	1327	26	313	226	SB	180										getting hot, sunny
	1334	23	305	315	NB		168									
	1341	22	309	308	SB	192										
	1351	25	303	210	NB		180									
	1356	23	315	305	SB	204										
	1406	21	301	317	NB		192									
	1410					204	192	0.32	0.34	0.28	0.37	0.37	0.29	0.4	0.45	
	1412	25	210	303	SB	216										
	1420	24	312	222	NB		204									
	1427	21	317	301	SB	228										
	1432	26	313	226	NB		216									
	1442	24	222	312	SB	240										
	1448	22	309	308	NB		228									
	1456	26	226	313	SB	252										
	1459	27	306	SC	NB		232									
	1508	27	306	SC	SB											
	1510	23	315	305	NB											

1C-8

										Tribo						
6/16/2004	Date-time	Consist	Lead	Trail	Direction	SB Wheels	NB Wheels	TORHNB	TORLNB	HNBGAGE	TORHSB	TORLSB	HSBGAGE	20' TORHNB #13	20' TORLNB #13	COMMENTS
	715															Setup
	800															Calibration
	805	X	X	X	SB											
	810	X	X	SC	NB											
	820							0.4	0.48	0.34	0.58	0.6	0.37	0.48	0.46	
	822	X	X	SC	SB	6										
	825	X	X	X	NB		12									
	829	21	311	317	SB	18										
	835	26	315	305	NB		24									No B&K Data
	840	24	210	303	SB	30										No B&K Data
	853	22	226	313	NB		36									
	858	26	305	315	SB	42										
	904	23	304	310	NB		48									
	913	22	313	226	SB	54										
	920	X	X	X	NB		60									
	928	23	310	304	SB	66										
	934	21	311	317	NB		72									Grease "B" installed
	943	25	309	308	SB	78										
	949	24	210	303	NB		84									
	957	21	317	311	SB	90										
	1005	26	305	315	NB		96									No B&K Data
	1016	24	303	210	SB	102										
	1019	22	313	226	NB		108									
	1029	26	315	305	SB	114										
	1034	23	310	304	NB		120									
	1044	22	226	313	SB	126										
	1052	25	309	308	NB		132									
	1059	23	304	310	SB	138										
	1106	21	317	311	NB											Warming up
	1114	25	308	309	SB											
	1120	24	303	210	NB			0.34	0.37	0.3	0.42	0.55	0.3	0.49	0.52	
	1130	X	X	X	SB											
	1134	26	315	305	NB											
	1143	24	210	303	SB											
	1150	22	226	313	NB											
	1157	26	305	315	SB											
	1211	X	304	310	NB											
	1214	22	313	226	SB											
	1219	25	308	309	NB											
	1227	23	310	304	SB											
	1230							0.3	0.38							Spot Check NB Rail
	1233	21	311	317	NB											
	1304															
	1310															
	1320															
	1326															
	1341															
	1349															
	1357															
	1400							0.3	0.3	0.33	0.35	0.3	0.37	0.42	0.48	

APPENDIX D

WEATHER SUMMARY

THE PORTLAND CLIMATE SUMMARY FOR JUNE 7 2004 . . .

TEMPERATURE (F)
MAXIMUM 66 253 PM
MINIMUM 52 607 AM
PRECIPITATION (IN)
YESTERDAY 0.08
RELATIVE HUMIDITY (PERCENT)
HIGHEST 89 M400 AM
LOWEST 45 M200 PM
AVERAGE 67

THE PORTLAND CLIMATE SUMMARY FOR JUNE 8 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 67 334 PM
MINIMUM 55 801 AM
PRECIPITATION (IN)
YESTERDAY 0.37
RELATIVE HUMIDITY (PERCENT)
HIGHEST 93 1200 AM
LOWEST 63 M400 PM
AVERAGE 78

THE PORTLAND CLIMATE SUMMARY FOR JUNE 9 2004 . . .

TEMPERATURE (F)
MAXIMUM 63 212 PM
MINIMUM 56 1116 AM
PRECIPITATION (IN)
YESTERDAY 0.14
RELATIVE HUMIDITY (PERCENT)
HIGHEST 100 1000 AM
LOWEST 72 M900 PM
AVERAGE 86

THE PORTLAND CLIMATE SUMMARY FOR JUNE 10 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 62 303 PM
MINIMUM 54 1159 PM
AVERAGE 58
PRECIPITATION (IN)
YESTERDAY 0.04
RELATIVE HUMIDITY (PERCENT)
HIGHEST 100 M200 AM
LOWEST 48 M200 PM
AVERAGE 74

THE PORTLAND CLIMATE SUMMARY FOR JUNE 11 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 61 653 PM
MINIMUM 53 814 AM
PRECIPITATION (IN)
YESTERDAY T

RELATIVE HUMIDITY (PERCENT)
HIGHEST 77 M200 AM
LOWEST 57 M200 PM
AVERAGE 67

THE PORTLAND CLIMATE SUMMARY FOR JUNE 12 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 68 344 PM
MINIMUM 51 310 AM
PRECIPITATION (IN)
YESTERDAY T
RELATIVE HUMIDITY (PERCENT)
HIGHEST 83 M300 AM
LOWEST 42 M300 PM
AVERAGE 63

THE PORTLAND CLIMATE SUMMARY FOR JUNE 14 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 67 420 PM
MINIMUM 53 505 AM
PRECIPITATION (IN)
YESTERDAY T
RELATIVE HUMIDITY (PERCENT)
HIGHEST 83 M500 AM
LOWEST 42 M400 PM
AVERAGE 63

THE PORTLAND CLIMATE SUMMARY FOR JUNE 15 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 76 423 PM
MINIMUM 52 531 AM
PRECIPITATION (IN)
YESTERDAY 0.00
RELATIVE HUMIDITY (PERCENT)
HIGHEST 77 M300 AM
LOWEST 31 M200 PM
AVERAGE 54

THE PORTLAND CLIMATE SUMMARY FOR JUNE 16 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 88 330 PM
MINIMUM 50 500 AM
PRECIPITATION (IN)
YESTERDAY 0.00
RELATIVE HUMIDITY (PERCENT)
HIGHEST 74 M500 AM
LOWEST 20 1200 PM
AVERAGE 47

THE PORTLAND CLIMATE SUMMARY FOR JUNE 17 2004 . . .

TEMPERATURE (F)
YESTERDAY
MAXIMUM 91 419 PM
MINIMUM 55 441 AM
PRECIPITATION (IN)
YESTERDAY 0.00
RELATIVE HUMIDITY (PERCENT)
HIGHEST 72 M300 AM
LOWEST 23 1200 PM
AVERAGE 48

APPENDIX E

SUMMARY OF FINITE ELEMENT ANALYSIS STUDY OF DRILLED HOLE IN 115 RE RAIL SECTION

Load Applied to Center of Rail Head

Assumptions

- Hole diameter: 0.1863 inch angled at 30 degrees from the vertical axis
- Hole is located equal distance between adjacent ties
- Vertical force applied to center: 20,000 pounds
- Rail section is in "non-worn" condition
- Distance between ties: 19.5 inches
- Vertical force applied equal distance from adjacent ties

Results

With a 20,000-pound vertical force applied at the center of the railhead, the nominal maximum tensile stress in the base of a 115 RE rail section would be about 6,100 psi. See Figure E1. With the introduction of the lubrication hole, however, an area of concentrated stress is created in the inner diameter (Figures E2 and E3). This stress value is calculated to be about 21,000 psi—an increase of about 3.44 times the nominal value for a standard 115-pound rail. If a dynamic load factor 2.0 were considered, the maximum stress would be increased to about 42,000 psi. If the ultimate tensile strength of the rail head were about 187,000 psi, and the infinite life fatigue strength were estimated at 74,800 psi (40 percent of tensile strength), the introduction of the 42,000-psi stress concentration would not result in any significant fatigue damage.

Combined Lateral and Vertical Load Applied at Hole

- Diameter of load application area over hole: 0.250 inch
- Combination of vertical and lateral force: 19,000 pounds vertical, 14,355 pounds lateral
- Finite element model uses elements with linear stress strain properties only

Results

The most significant result from this load case is that the bearing stress around the edge of the hole could be very high (Figure E4). The actual stress level would not be nearly as high as shown in Figure E4 but would still likely be high enough to result in localized yielding and plastic deformation. The deformation would result in a redistribution of the stress around the hole. A bevel on the edge of the hole would probably be desirable to not only reduce the concentrated bearing stresses but also reduce the possibility of cracks being initiated at the sharp edge of the hole.

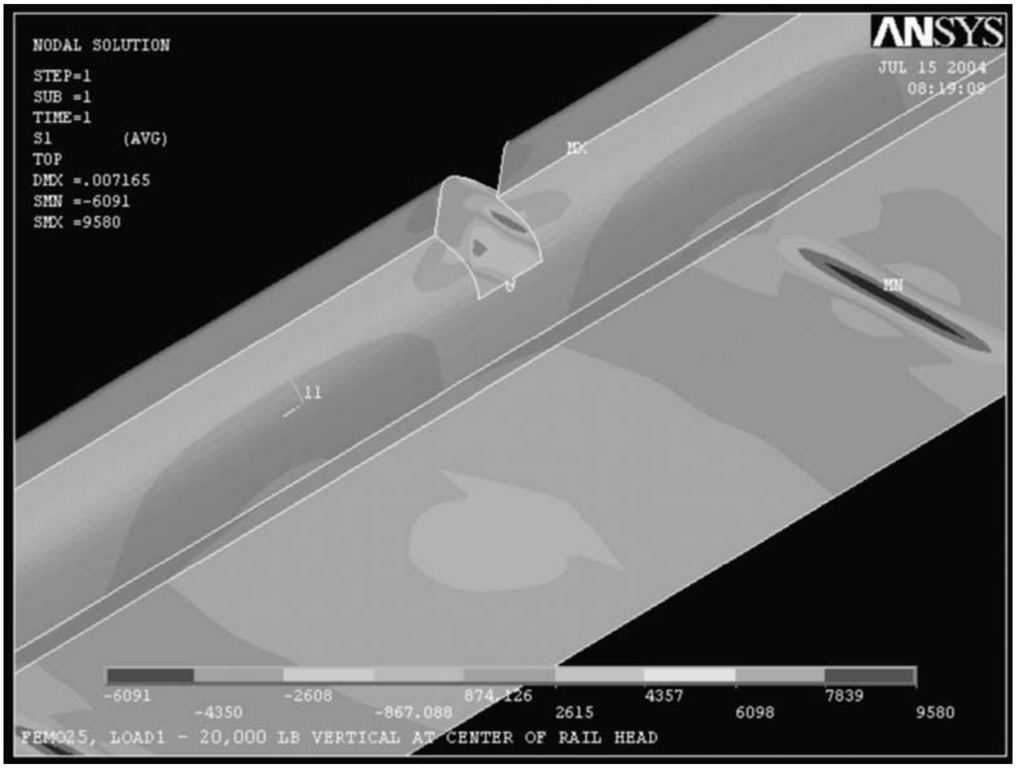

Figure E1. Highest Nominal Tensile Stress Normally in Base of Rail—Maximum Principal Stress of 6,100 psi with 20,000 Pounds Vertical Force Applied at Center of Rail

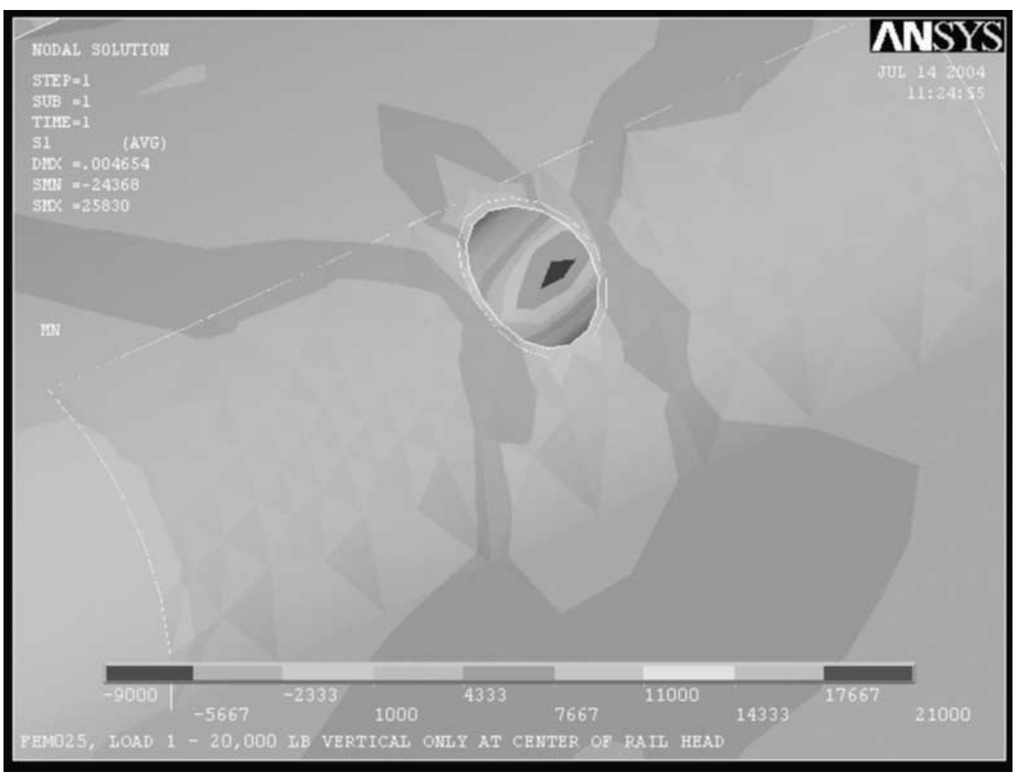

Figure E2. Stress Concentration in Hole—Maximum Principal Stress of 21,000 psi with 20,000 Pounds Vertical Force at Center of Rail Head

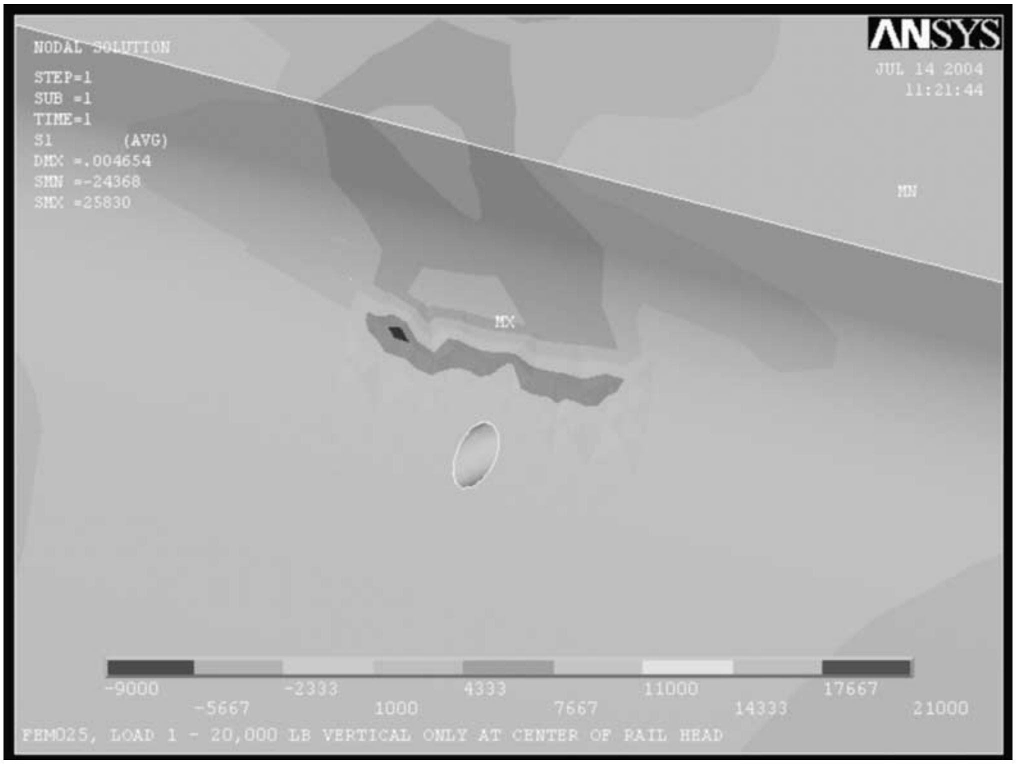

Figure E3. Maximum Principal Stress at Lower End of Hole—20,000 Pounds Vertical Force Applied at Center of Rail Head

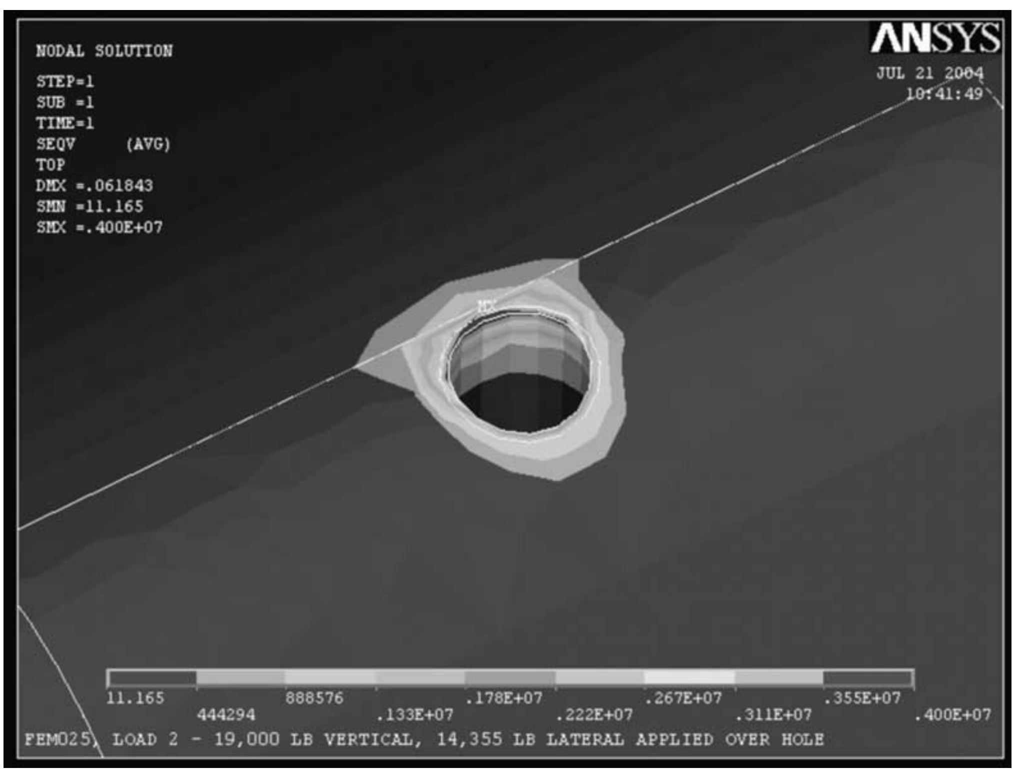

Figure E4. Von Mises or Equivalent Stress if Combined 19,000-Pound Vertical and 14,355 Lateral Forces Concentrated in Area of Hole Assumes No Yielding of Material

ATTACHMENT 2:

New Jersey Transit Newark Subway Observations and Data from Demonstrating Top-of-Rail, Onboard Applicator Using Friction Modifier

SUMMARY

Proper application of the friction control product produced a top-of-rail (TOR) friction range of 0.30 μ to 0.35 μ and resulted in no adverse effect on braking distance or wheel slip control systems. This evaluation was conducted on tangent track; thus, the effect on noise was not measured. Additional testing with excessive application of the material resulted in friction values below 0.25 μ and increased braking distance, which also caused the automatic wheel slip protection system to activate.

During and after TOR application, a left-to-right rail friction differential was noted, suggesting that the two nozzles were not applying material in the same amount or to the same location on the wheels. This indicates that the application system configuration and adjustment are critical to ensure that proper left-to-right rail balance of rail friction control is achieved.

This evaluation was limited to slow speed application and braking modes. Additional evaluations at higher speeds and with a variety of other trains, curves, and tangent and rail profiles are needed to properly specify implementation guidelines. The collected data and test configuration were not sufficient to specify an implementation/deployment plan or to determine how many cars in the fleet would need to be equipped.

BACKGROUND

New Jersey Transit (NJT) is investigating application systems and products to obtain TOR friction control for reducing noise and wear. Applying friction modifiers to the TOR using an onboard application system offers some advantages over wayside/fixed systems. It is being considered for a future extension that will utilize street and/or paved track. Previous evaluations by NJT using a friction modifier applied by hand (i.e., roller) indicated no adverse effect on braking distances.

Recently NJT has been evaluating a modified onboard flange lubrication system to apply friction modifier to combat noise and vibration. It has been suggested that this application system can be configured to apply material to the TOR as well as the back of wheel, thus further reducing noise and vibration on street trackage without the need for wayside applicators.

As a preliminary screening test to ensure safety, a limited evaluation was conducted to measure rail friction, braking distance, and wheel slip control reaction to the friction control material. Results of this demonstration show that, when the material is properly applied, no adverse braking or wheel slip conditions were created. However, when excessive material was purposely applied, friction fell below 0.20 μ, causing wheel slip during braking and acceleration. TTCI observations and participation for this demonstration were funded as part of a Transit Cooperative Research Program effort to document innovative rail/wheel friction control practices used in the transit industry.

Results of this screening demonstration were not intended to encompass all issues and are not sufficient for approving use of this product in a full implementation mode. The testing was conducted on a slow-speed (15-mph) yard section. It did not include evaluations over curved track, nor did it include data to document noise reduction. Due to time and budget issues, observations were limited only to measuring changes in rail friction and braking system operation. Results suggest that success can be reached with proper control of application. NJT may elect to conduct more rigorous and controlled testing to evaluate stopping distance and noise reduction performance from higher speeds and under a greater variety of train and track conditions.

TEST CONDITIONS AND CONDUCT

A 700-foot tangent section of track located in the Grove Street covered car storage facility was made available for testing on July 21, 2004. Because the middle of three tracks was used, conflicts with equipment stored on adjacent tracks were avoided. Also, the center track is used regularly for storing trains at night and during off-peak times; thus, it was reasonably shiny and rust-free. Outside storage tracks would have required significant cleaning and polishing to remove surface rust.

There were two major limitations of the site and test: all track was tangent and had a maximum speed limit of 15 mph. In yard mode, an overspeed warning system fitted to each car activated a buzzer if speed exceeded this limit. Train operations were limited to one car operating back and forth over this tangent; thus, no curving or creepage at the wheel/rail interface was achieved. The applicator system was active only on forward moves. Backup moves were conducted with no active application of friction control material.

The test was conducted as follows, with details outlined in the next section:

- Clean rail of dust and sand by operating multiple passes of a single vehicle
- Conduct several braking tests to document wheel slip protection (WSP) operation
- Apply TOR friction control material using multiple passes with the car
- Conduct braking tests to determine the effect on WSP operation
- Operate a limited number of extra passes to observe performance under higher levels of material
- Clean rail to remove materials by sanding

VEHICLE MODIFICATIONS

Car Number 117 is equipped with a flange and back-of-wheel lubricator system. Prior to testing, the B-end system was drained and a reservoir was filled and the system purged.

The B-end flange nozzles were reconfigured to apply material to the wheel tread, with the back of wheel nozzles remaining as normal. A test of the system to provide a sample spray pattern was conducted prior to moving the car to ensure that equal amounts of product were applied to each wheel tread.

The flange system on Axle 6 was modified to apply friction control material onto the wheel tread. As a backup, the applicator for Axle 1 was also adjusted for the TOR in case time allowed demonstrating the standard product used for flange lubrication. Time, however, did not allow such a demonstration.

The application rate for the system as configured is adjusted by time "on" and time "off." The amount of product applied during the time "on" is not adjustable; thus, the vehicle speed will affect the amount of product applied per mile of travel at any given on-off cycle setting.

Initial timing was set for 6 seconds "on" and 12 seconds "off." Onboard observations of the system function during the test indicated that the "on" cycle started immediately after forward motion of the car was detected and ceased whenever wheel motion was stopped.

TEST SEQUENCE

A test plan was prepared prior to testing and the general plan and sequence were agreed upon by NJT personnel. The test/demonstration was conducted on July 21, 2004, between 9 a.m. and 1 p.m. at the Grove Street yard facility.

After final adjustments and inspections were conducted over the pit in the maintenance facility, the car was relocated under its own power to the covered storage facility building.

Initial inspection of the center track indicated a slightly dusty rail condition due to sand dropped from stopped vehicles. Several spot tribometer readings were made showing the rail to read about 0.55 μ to 0.65 μ. Such high readings indicate very dry rail conditions.

Ten test configurations were conducted or measured as follows:

1. Initial "as is" rail inspection: TOR friction was measured using a hand tribometer with readings showing a range of 0.55 μ to 0.65 μ. The rail surface was shiny, but covered with dust and ground sand.

   A test zone was designated near the middle of the 700-foot tangent for repeating tribometer measurements and for specifying a braking zone. This area was adjacent to the center crosswalk in the storage facility building.
2. Cleaning passes: The NJT Number 117 test car was operated for five round trips (10 passes) to clean the rail and remove loose dust and sand. The rail friction was re-measured after completion of these operations.

   TOR friction values after cleaning:

   North Rail: 0.59 μ
   South Rail: 0.61 μ
3. Dry rail braking tests: The sanding system was disabled for the remaining testing period to prevent sand application from affecting friction readings. A braking marker point was established for the operator to apply full-service braking while approaching the observation site. Each braking run was initiated by backing the vehicle to the starting point at the end of the storage shed, then approaching the test point at a speed not to exceed 15 mph. An audible warning system was activated when vehicle speeds exceeded 15 mph; thus, braking tests occurred between about 14 and 15 mph.

   A full-service application was made at the braking marker, and the vehicle was allowed to stop. During the braking period, the operator and onboard observers noted any indication of automatic WSP control activation by monitoring the indicator light.

   Dry rail braking distance was approximately 60 feet from the marker.

   During several braking runs the stopping point was noted within 1 foot of the crosswalk. No WSP activation occurred during dry braking other than a brief indication just prior to the final 2 feet of motion.

   Final TOR friction values after dry rail braking tests were:

   North Rail: 0.61 μ
   South Rail: 0.65 μ
4. TOR system activated, product applied over two passes: The TOR system was activated after the car was relocated to the west end of the test zone. Two round trips over the entire 700-foot test zone were made at 15 mph, applying product only on the eastbound direction. The application rate remained 6 seconds on, 12 seconds off.

   TOR friction measured after two passes:

   North Rail: 0.46 μ
   South Rail: 0.44 μ

   Two additional round-trip passes were made, again applying product only in the eastbound direction. Friction was then measured in two locations. The primary location as above, and about 30 feet westward, closer to the starting point:

	Primary Location	30 feet West of Primary Location:
North Rail:	0.41 μ	0.30 μ
South Rail:	0.35 μ	0.20 μ

5. Braking tests conducted on rail with friction modifier applied: The onboard system was deactivated to conduct braking tests over rail with friction values shown above.

   The stopping distance was not changed, and both runs stopped within 1 foot of the dry rail location. Also, no indication of the WSP activation was observed during braking runs other than the short indication during the last 2 feet of operation as under dry rail.

Final friction values after four applicator passes and two braking runs:

North Rail: 0.33–0.35 μ

South Rail: 0.35–0.36 μ

6. It was then decided to operate five passes with various output rates, starting the system at different locations. This would spread the product more uniformly over the short zone. The first two passes were made with manual operation of the system, while the last three were conducted with the system left on automatic.

   Friction after the five additional passes:

   North Rail: 0.30–0.31 μ

   South Rail: 0.16–0.17 μ
7. Braking tests were then conducted on the rail after these five additional passes. The first braking test resulted in about 20 feet of additional distance required to stop, with the WSP indicator on for the entire run. A second braking test was conducted with similar results and full WSP indication.

   The rail friction was then re-measured:

   North Rail: 0.45 μ

   South Rail: 0.31 μ

   Two additional braking tests were conducted. Both indicated full WSP for the entire distance, with stopping distances 10 to 15 feet longer than dry.
8. The onboard TOR system was then deactivated and two round trips were conducted to dry off the rail and more evenly spread friction control material. Two braking tests were then conducted. Both exhibited continuous WSP and resulted in stopping distances about 10 feet longer than under dry rail conditions.

   The rail friction was then re-measured:

   North Rail: 0.29 μ

   South Rail: 0.21 μ
9. The vehicle was then moved to the outside yard and operated over several curved track areas to dry wheels and remove friction control material. Due to the track configuration, the vehicle had to operate over the 700-foot test zone to return to the starting point for braking tests. Two braking tests were conducted, with stopping distance about 5 feet and 4 feet longer than dry, with WSP indications on through most of the braking run.

   No friction measurements were taken.
10. Final rail cleaning efforts: The rail conditions and crew time dictated that no additional testing with other products was feasible that day before the car was needed for revenue service. The rail was then dried by operating one slow pass while manually activating the sanding unit. This was followed by three additional passes with no additional sand applied to spread and grind the sand onto the surface.

    Two braking tests were conduced on this dry rail. Both stopped at or before the location of the initial dry rail tests and no WSP indications were observed.

    Final rail friction was then measured:

    North Rail: 0.55–0.59 μ

    South Rail: 0.44–0.55 μ

RESULTS

Under normal application rates with a small level of product application, the TOR friction remained in the range of 0.30 μ to 0.35 μ. These values did not adversely affect braking distance, nor did they cause any additional WSP activation.

When the application was excessive, the braking distance was adversely affected, increasing stopping distance from 60 feet to about 80 feet at 15 mph.

Once application of TOR material started, the south rail routinely exhibited lower friction readings than the north rail, suggesting a slight difference in location of application, amount of product, or other anomalies affecting friction on the rail. This bias was noted after the initial passes and remained even after the final dry-down when the south rail continued to show a lower friction value than the high rail.

CONCLUSIONS AND RECOMMENDATIONS

Proper and consistent application of the friction control material is essential to avoid creating a condition leading to wheel slip and braking issues. While proper application did not affect braking distance, the effect on noise was not measured because all tests were conducted on tangent track. During the testing no squeal or high-pitch noise was observed under any condition.

During and after TOR application, a left-to-right rail friction differential was noted, suggesting that the two nozzles were neither applying the same amount of product nor applying to the same location. While static tests of the spray pattern and location on the wheel were conducted during vehicle setup, the actual location on the wheel where material is applied may be different under dynamic conditions. Thus, tests at speed may be needed to determine static adjustment requirements. This evaluation was limited to slow-speed application and braking modes. Additional evaluations at speeds up to 50 mph and with a variety of other trains, curves, tangent lengths, and rail profiles are needed to properly define implementation guidelines. An implementation plan may include equipping one car to all of the car fleet; however, the effect of multiple passes of non-equipped trains must be determined to properly deploy a fleet.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation