Train Resistance and Railroad Emissions and Efficiency

Mark Stehly
October 24, 2008
About BNSF

- Headquartered in Fort Worth, Texas; operates in 28 states and two Canadian provinces
- Employs more than 40,000 people nationwide, with major Southern California operations in Los Angeles, San Bernardino and Barstow
- BNSF is North America’s largest grain-hauling railroad and also carries plastics, building and construction materials and consumer goods.
- Moves more intermodal traffic than any other rail system in the world
BNSF System & Revenue

Freight revenue and % change from 2006

$ Millions

- **Industrial Products**: $3,684
  - +2.6%
- **Consumer Products**: $5,664
  - +0.9%
- **Coal**: $3,279
  - +12.4%
- **Ag**: $2,722
  - +12.2%

2007 Total BNSF Freight Revenue: $15,349 +5.5%

One of the largest North American railroads
32,000 route miles, covering 28 states and two Canadian provinces

- Consumer Products: $5,156
  - +21.5%
- Industrial Products: $3,684
  - +17.3%
- Ag: $2,722
  - +12.2%
- Coal: $3,279
  - +12.4%

- **Port of Seattle**
- **S. Seattle**
- **Port of Tacoma**
- **Port of Portland**
- **Spokane**
- **Billings**
- **Dilworth**
- **St. Paul**
- **Chicago (Gibson)**
- **Chicago (Corwith)**
- **Chicago (Willow Springs)**
- **Logistics Park Chicago**
- **Kansas City, KS**
- **Kansas City, MO**
- **St. Louis**
- **Omaha**
- **Denver**
- **El Paso**
- **Alliance**
- **Barbour’s Cut**
- **Houston**
- **New Orleans**
- **San Diego**
- **Phoenix**
- **Albuquerque**
- **Amarillo**
- **Harvard**
- **Memphis**
- **Atlanta**
- **Birmingham**
- **Richmond**
- **Oakland (OIG)**
- **Los Angeles**
- **Port of Long Beach**
- **Port of Los Angeles**
- **Port of Seattle**
Topics

- Train resistance
  - Wheel/rail interaction and bearing drag
  - Aerodynamic drag

- Criteria air pollutants from locomotives and railyards
  - Non-attainment areas
  - Locomotive contribution to inventories

- Fuel efficiency
- System efficiency and locomotive efficiency
- Greenhouse gas emissions
Train Resistance

- Train resistance is a quadratic equation.

- \( R = A + BV + CV^2 + \text{curving} + \text{grade} + \text{acceleration} \)

- A is wheel bearing drag and wheel/rail friction.

- B is track bed deformation and is nearly zero.

- C is aerodynamic drag having the velocity with respect to the wind.

- R is in lbs force or lbs force per ton of train weight.
Bearings require that a torque be applied for movement. Bearing drag with a rubbing seal typically is 10 lbs force per bearing at a typical wheel size. This is 0.6 lbs force per ton of train weight. Removal of the seal reduces bearing drag by 50%. New labyrinth seals which are non-rubbing can reduce bearing drag by 30% or more.

Wheel/rail friction on tangent track without lubrication typically is 2 lbs force per ton of train weight.
Wheels and Bearings
Effect of Gage Face Lubrication Levels on Gage Face Wear Rate in Curves With Std Rail

Gage Face Wear Rate
Inches/1000 MGT

Degree of Lubrication

COF 0.50
COF 0.35
COF 0.30
COF 0.20
Portec High Speed Tribometer
Full Scale Train Resistance Testing

Five miles of continuous tangent track with 14 feet of rise
Top-of-Rail Lubrication
Lateral Force Measurements, Average of Leading Axles Both Rails, All Cars

Pre Lubrication vs. Post Lubrication

LATERAL FORCE, kips

PERCENT OCCURRENCE

Post Lubrication

Pre Lubrication

11/21/01-01/16/02
01/18/02-03/07/02
Aerodynamic Drag

- C is the aerodynamic drag having the velocity with respect to the wind.

- \[ C = \frac{1}{2} \rho \times C_d \times A_f \]

- \( \rho \) is the air density

- \( C_d \) is the drag coefficient.

- \( A_f \) is the frontal area.

- Drag is often reported as Drag Area per 100 square feet of frontal area.
Wind Tunnel Testing of a Covered Coal Car
Comparison of Wind Tunnel and Full-Scale, covered hopper cars

Drag Area, in feet squared

- Wind Tunnel: 29.4
- Wind Tunnel: 28.2
- Full Scale: 28.3
- Full Scale: 31
Comparison of Wind Tunnel and Full-Scale, open top and covered gons with 5 degree yaw

Drag Area, in feet squared

- Covered, Wind Tunnel: 31.7
- Covered, Full Scale: 20.3
- Open Top, Empty, Wind Tunnel: 79.4
- Open Top, Empty, Full Scale: 74.9
Effect of Gap Size on Aerodynamic Drag, trailer on a spine car in a wind tunnel

![Graph showing the effect of gap size on drag area.](image)

- **Drag Area, in square feet**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50

- **Gap Size in inches**
  - 10
  - 42
  - 70
  - 107
  - 140
Other Train Resistance Factors

- Curving typically is 0.8 lbs force per ton per degree of curvature. A 5 degree curve would result in 4 lbs force per ton of train weight.

- Grade is the resistance due to gravity acting on the train mass. The resistance is 20 lbs of force per ton of train weight for a 1 percent grade.

- Acceleration requires a force of 91 lbs per ton per mile per hour per second. A train accelerating at 10 miles per hour per minute would require a force of 15 lbs per ton. This is equivalent to a 0.75% grade.
Sources of Train Resistance

- Aerodynamic
- Rolling
- Grade
- Curving

Train Speed in miles per hour

Resistance in lbs force per ton of weight

2 deg curve, 0.5 percent grade
Intermodal Train Fuel Consumption By Cause

- Aerodynamics: 30%
- Grade: 40%
- Rolling, Bearing, Curving: 20%
- Acceleration: 10%
FUEL ENERGY USES AND LOSSES

- Diesel to Mechanical Conversion: 60%
- Main Generator - Mech. To Elec.: 4%
- Accessory Horsepower: 2%
- Traction Motor & Gearbox - Elec. To Mech.: 7%
- Aerodynamic Drag: 8%
- Grade Change: 11%
- Acceleration: 3%
- Rolling, Bearings, Curves: 5%
- Drawbar: 27%

Diesel engine efficiency based on SD70MAC at full load. Division of Drawbar horsepower representative of intermodal service.
Ozone Non-Attainment Areas

Source: US EPA, Office of Air and Radiation, AIRS Database
So. California Historical Air Quality
SCAQMD NOx Inventories

Data Source: ARB – Almanac Emission Projection Data (Published in 2005).

Diesel Trucks – LHDD1, LHDD2, MHDD, HHDD
SCAQMD PM2.5 Inventories

Data Source: ARB – Almanac Emission Projection Data (Published in 2005).

Diesel Trucks – LHDD1, LHDD2, MHDD, HHDD

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
<th>2010</th>
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<tr>
<td>Diesel Trucks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offroad Equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ships &amp; Commercial Boats</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trains</td>
<td></td>
<td></td>
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</table>

% SCAQMD NOx Inventory

<table>
<thead>
<tr>
<th></th>
<th>% SCAQMD NOx Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>3.2%</td>
</tr>
<tr>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td></td>
<td>5.6%</td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>0.8%</td>
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</table>
Overall Picture

Temperatures

350 K

Cold Fuel

950 K

Rich Fuel/Air Mix $\phi \sim 4$

825 K

Products of Rich Combustion CO, UHC & Particulates

~1600 K

NO$_x$

~2700 K

CO$_2$ & H$_2$O

Chemistry

Warm Air

SAE Paper 990509
NOx Vs Combustion Temperature

Peak Flame Temperature (K)

fsNOx (g/kg Fuel)

X2 NOx

75 K
Evolution of Engine Emission Control

- 1974 EPA (HC + NOx)
- 1988 Models
  - Retard Timing
  - Inc. Inj. Press
  - Higher Boost
  - Higher CR

- 1987 Models
  - Retard Timing
  - Lower IMT
  - Shorten HRR
  - Low Friction

Tier 1
- Cooled EGR
- 1990
- 1991 Models
  - Retard Timing
  - Low IMT/High IMP
  - Inc. Inj. Press.
  - Variable Inj. Timing

Tier 2
- 1991
- 2004

NOx (g/(HP-hr)) @ 1000 RPM

Particulate [g/(HP-hr)]
## Inherent Efficiencies of Rail

<table>
<thead>
<tr>
<th></th>
<th>1 double stack train equals volume of up to 280 trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Efficiency</strong></td>
<td>Trains are <strong>2-4 times more fuel efficient</strong> than trucks on a ton-mile basis</td>
</tr>
<tr>
<td><strong>NOx Emissions</strong></td>
<td>Trains are <strong>2-3 times cleaner</strong> than trucks on a ton-mile basis</td>
</tr>
</tbody>
</table>
NOx Emissions per ton Mile of Freight South Coast Air Basin

![Graph showing NOx emissions trend from 2005 to 2040 for trucks and rail. The graph indicates a decrease in NOx emissions over time, with trucks showing a more significant decrease compared to rail.](image-url)
PM Emissions per ton Mile of Freight South Coast Air Basin

Calendar Year

PM Emissions (g/ton-mile)

Trucks

Rail

2005 2010 2015 2020 2025 2030 2035 2040
## Comparison of Mobile Source Requirements
(South Coast Inventory 2010)

<table>
<thead>
<tr>
<th></th>
<th>Trucks</th>
<th>Off-Road Equipment</th>
<th>Ships</th>
<th>Aircraft</th>
<th>Urban Buses</th>
<th>Loco-motives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inventory NOx/PM</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Standards for New Units</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Retrofit Existing Units</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Rebuild to New Standards</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>NOx Fleet Avg. in SCAQMD</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Statewide PM 2005 MOU</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
South Coast Fleet Average

Reductions from EPA Loco. Tiers 1 and 2 only … continental US

Reductions when Loco. Tier 0 added to Tiers 1 and 2 … continental US

67% NOx reduction from South Coast Fleet Average Program in Southern California!

Southern California commitment from the Railroads
Work Done By Train Type, in percent

- Yard Switchers: 12%
- Merchandise: 5%
- Intermodal: 19%
- Road Switchers: 64%
Switcher Locomotives

Green Goat® Locomotives
- “Hybrid” light-medium duty switcher
- Reduces fuel consumption and atmospheric emissions by 60 percent
- Emits 80 to 90 percent fewer pollutants than conventional train engines
- Batteries recharged by 290 HP EPA off-road Tier 2 diesel gen set (significantly exceeds EPA locomotive Tier 2 requirements)

Liquefied Natural Gas Locomotive
- BNSF operates the only four environmentally friendly liquid natural gas locomotives that reduce emissions and fuel consumption
- 1200 sustainable horsepower, spark ignited

Multiple Gen Set Switcher
- Powered by multiple diesel gen sets with truck-like engines
- 700 sustainable horsepower from each gen set
- Typically 3 engines per locomotive
## Comparison of Existing and New EPA locomotive emission regulations, g/hphr

<table>
<thead>
<tr>
<th>Remanufacturing Tier</th>
<th>Original Build Date</th>
<th>Existing Nitrogen Oxides</th>
<th>New Reg Nitrogen Oxides</th>
<th>Existing Particulate Matter</th>
<th>New Reg Particulate Matter</th>
<th>Date required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled</td>
<td>1975</td>
<td>13.1</td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
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<tr>
<td>Remanufacturing tier 0</td>
<td>1973-1992</td>
<td>9.5</td>
<td>8.0</td>
<td>0.6</td>
<td>0.22</td>
<td>2008-10</td>
</tr>
<tr>
<td>Remanufacturing tier 0</td>
<td>1993-2002</td>
<td>9.5</td>
<td>7.4</td>
<td>0.6</td>
<td>0.22</td>
<td>2008-10</td>
</tr>
<tr>
<td>Remanufacturing tier 1</td>
<td>2003-2004</td>
<td>7.4</td>
<td>7.4</td>
<td>0.45</td>
<td>0.22</td>
<td>2008-10</td>
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<tr>
<td>Remanufacturing tier 2</td>
<td>2005-2011</td>
<td>5.5</td>
<td>5.5</td>
<td>0.20</td>
<td>0.10</td>
<td>2008-13</td>
</tr>
<tr>
<td>Tier 3</td>
<td>2012-2014</td>
<td>5.5</td>
<td></td>
<td>0.10</td>
<td></td>
<td></td>
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<tr>
<td>Tier 4</td>
<td>2015</td>
<td>1.3</td>
<td></td>
<td>0.03</td>
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EPA Locomotive Standards

EPA Line-haul Locomotive Standards
(% Reduction from Uncontrolled Levels)

<table>
<thead>
<tr>
<th>Tier 2</th>
<th>Tier 3</th>
<th>Tier 4</th>
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<tbody>
<tr>
<td>0%</td>
<td>-38%</td>
<td>-91%</td>
</tr>
<tr>
<td></td>
<td>-58%</td>
<td>-90%</td>
</tr>
</tbody>
</table>

Prepared by California Environmental Associates
Sources of Emissions at a Large Intermodal Yard

- Drayage trucks 40%
- Cargo handling equipment 20%
  - Cranes
  - Yard Tractors
- Linehaul locomotives (Arriving & Departing trains) 10%
- Transportation Refrigeration Units 10%
- Switch Engines 10%
- Adjacent Mainline Freight 5%
- Adjacent Commuter Rail 3%
- Other 2%
San Bernardino, California
Predicted reductions with 4% annual growth in activity
Typical drayage truck fleet turnover assumed (not CAAP)
New Intermodal Yard Green Technology

- Electric Rail-Mounted Gantry (RMG) cranes
  - Reduced air emissions, noise and light
- LNG (or equivalent) yard hostler tractors
- LNG, multi-engine or “hybrid” switch engines
- Low-sulfur fuel and idle shut-down feature for road locomotives
- Low emission drayage trucks
At the end of 2007

- Total fleet is 6800 locomotives
- Installed 3300+ locomotives with AESS
- Retrofit 2200 locomotives to Tier 0
- Purchased 620 Tier 1 locomotives
- Purchased 880 Tier 2 locomotives
- Fleet average nitrogen oxides emissions reduced 30% since 2000
- 2260 more locomotives to retrofit to Tier 0
- 900 locomotives pre 1973 (not subject to retrofit)
Locomotive Fuel Efficiency, medium duty cycle

net traction
KWH per gallon of fuel

Road Locomotive Hybrid Concept

Diesel Engine

Heat

Grid Resistors

Power Electronics

Energy Storage

Energy Management System

G(s)

Alternator Rectifier

Traction Motor

Braking

Motoring

Wheels & Rail
## Greenhouse Gas Emissions

<table>
<thead>
<tr>
<th>Year</th>
<th>GTM/Gal</th>
<th>Fuel Volume Gal</th>
<th>Million Tons of CO2</th>
</tr>
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<tbody>
<tr>
<td>1995</td>
<td>693.3</td>
<td>1,080,878,000</td>
<td>12.10</td>
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<tr>
<td>1999</td>
<td>734.4</td>
<td>1,187,305,000</td>
<td>13.29</td>
</tr>
<tr>
<td>2000</td>
<td>747.2</td>
<td>1,172,949,000</td>
<td>13.13</td>
</tr>
<tr>
<td>2001</td>
<td>760.4</td>
<td>1,177,144,000</td>
<td>13.17</td>
</tr>
<tr>
<td>2002</td>
<td>760.3</td>
<td>1,148,682,000</td>
<td>12.86</td>
</tr>
<tr>
<td>2003</td>
<td>751.2</td>
<td>1,213,409,000</td>
<td>13.58</td>
</tr>
<tr>
<td>2004</td>
<td>752.9</td>
<td>1,344,000,000</td>
<td>13.98</td>
</tr>
<tr>
<td>2005</td>
<td>756.9</td>
<td>1,402,000,000</td>
<td>14.75</td>
</tr>
<tr>
<td>2006</td>
<td>757.6</td>
<td>1,478,000,000</td>
<td>15.02</td>
</tr>
</tbody>
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Reducing Greenhouse Gases

- Reduce locomotive idling (install Idle Reduction Devices)
- Acquire new line haul locomotives (better fuel efficiency)
- Acquire new switch locomotives (GenSet multi-engine, and hybrid locomotives)
- Improve train performance through engineer training and evaluation programs
Reducing Greenhouse Gases

- Promote the use of Low Torque Roller Bearings
- Continue to improve wheel and rail lubrication
- Improve intermodal loading methods to reduce aerodynamic drag

From 1995 and 2006
11,066,000 tons of CO2 reduction
Summary

- Railroads are part of the environmental solution
- Railroads contribute to the problem and will achieve large reductions in emissions
- Railroads do more than other mobile sources
- Railroads are addressing needs around our yards
- If stationary sources were mobile, they couldn’t achieve their current reductions either