# Aerodynamic Drag Reduction of Open-Top Coal Cars in Unit Train Operation and Impact on Train Fuel Consumption and Economics


National Coal Transportation Association
Spring General Conference
26 – 29 April 2015
Litchfield Park, Arizona

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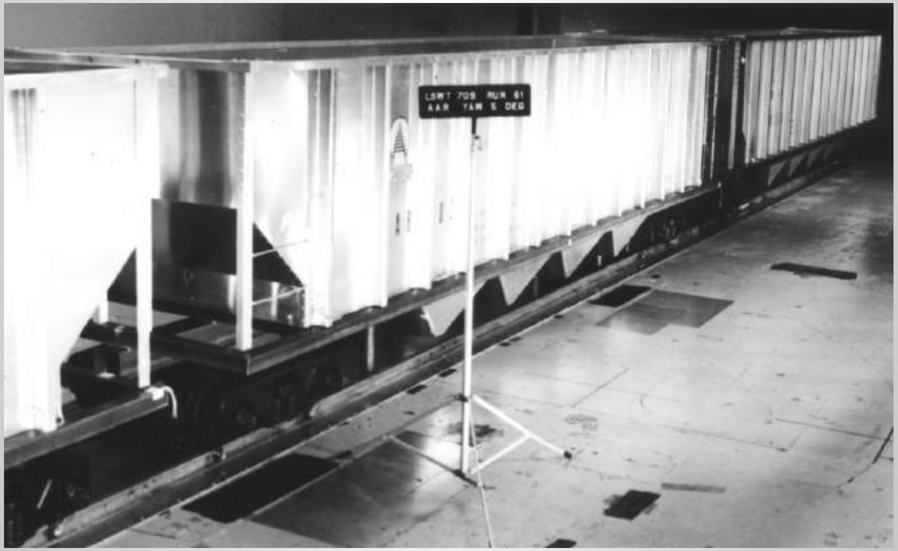
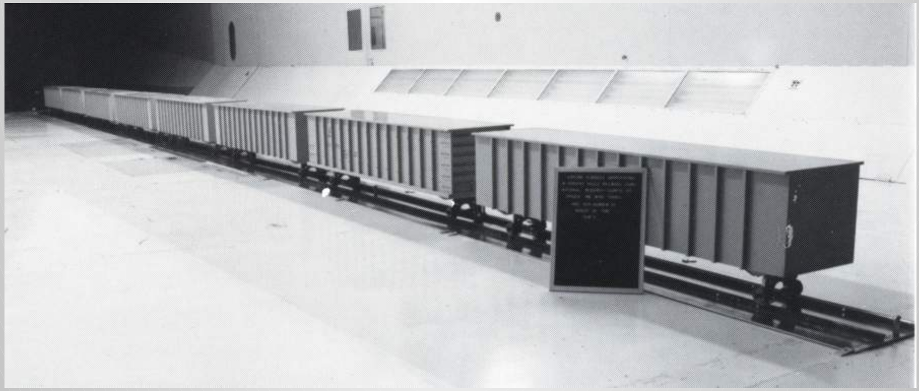



*30% scale baseline hopper car models in Lockheed Georgia Company wind tunnel at 5° yaw.*

## The current study involved two primary tasks:

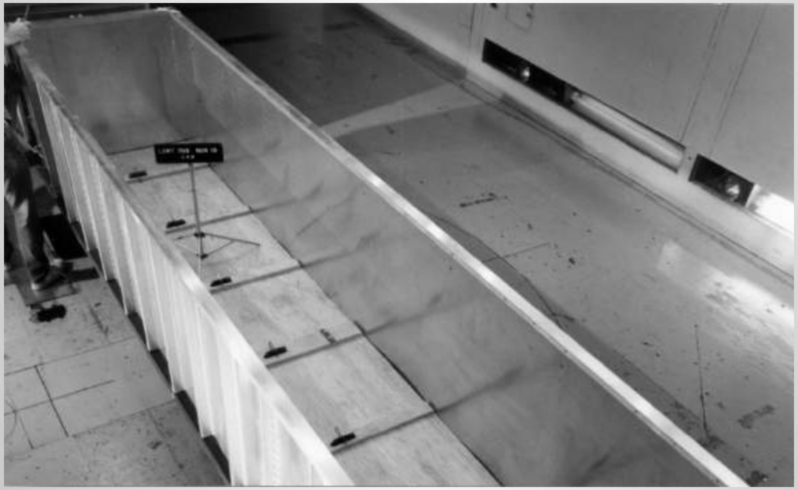
1) Identify and test candidate retrofit coal car **aerodynamic drag reducing devices** and rank the devices by
   - Effectiveness
   - Impact on train fuel usage
   - Return on investment
2) Build prototype drag reducing devices and test them at full scale to verify durability and fuel savings



*16% Scale Gondola Car Models in National Research Council of Canada 9 M Wind Tunnel (8 car train)*

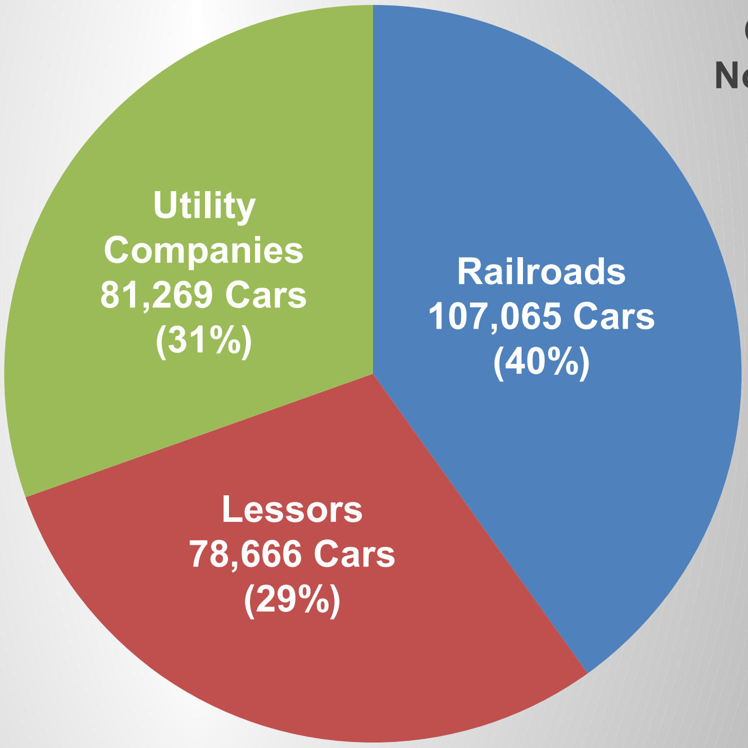
## Presentation Outline

- **Coal Car Aerodynamics**
- **Impact of Candidate Aerodynamic Devices on Train Fuel Economy**
- **Conclusions and Recommendations**



*30% Scale Model High-Side Gondola Car, No Internal Bracing, Lockheed Georgia Company Low Speed Wind Tunnel*

## Definition of North American Coal Car Fleet




Total Number of Coal Cars in North American Fleet: 267,000

***Summary of North American Coal Car Fleet Population and Ownership***

# Classifications of Aerodynamic Modifications for Open-Top Gondola and Hopper Cars

- Covers
- Internal Baffles
- Underbody
- Inter-Car Spacing and Gap Fillers
- Car Side Geometry
- End Treatments

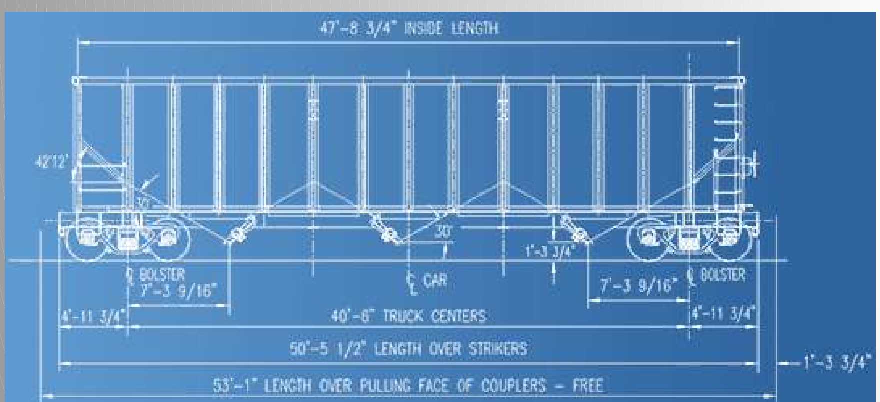



*Image: FreightCar America*

**Typical Hopper Car**


*Image: FreightCar America*

**Typical Gondola Car**

**Terminology:** It is convenient to group the drag coefficient and cross sectional area together and refer to them collectively as the **drag area**. This eliminates any confusion regarding the selected value for the cross sectional area.

**Drag Area** = $C_d$ A (ft$^2$)

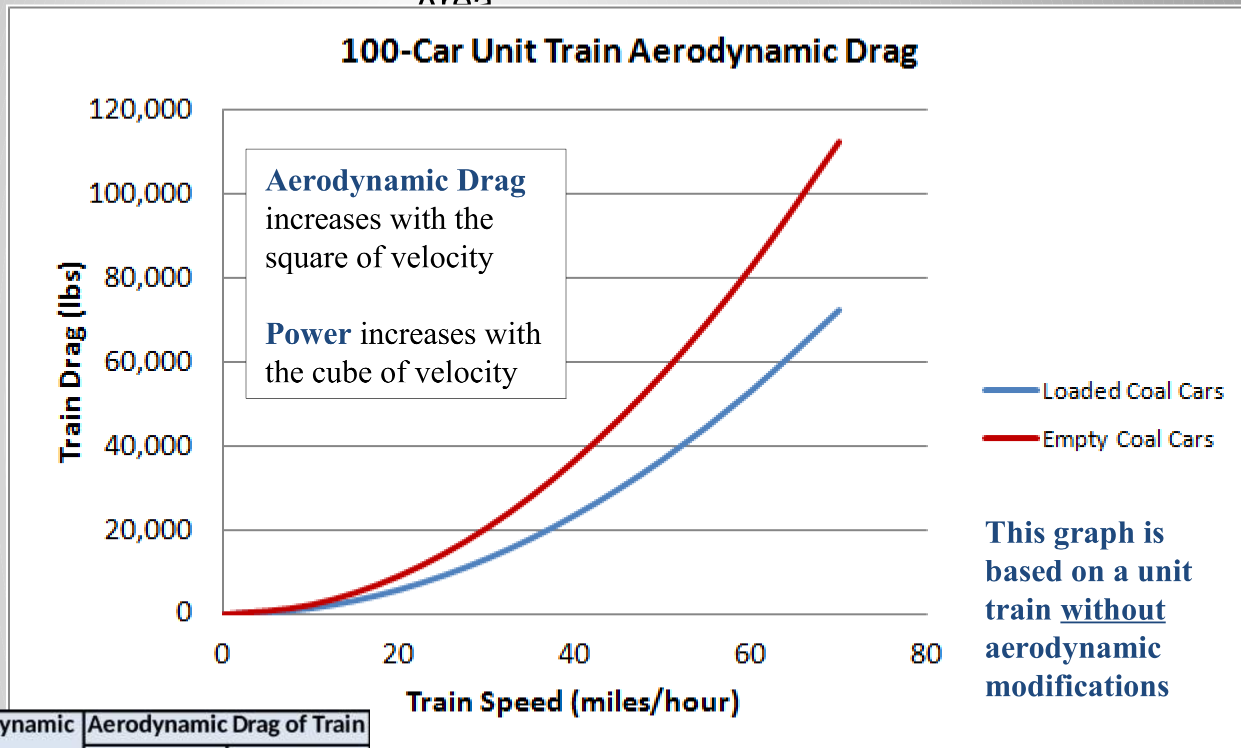
from: **$C_d$ = D /A q**

where:
D = Drag Force (lbs)
$C_d$ = Drag Coefficient (non-dimensional)
A = Cross Sectional Area of Coal Car (ft$^2$)
q = Dynamic Pressure of Air = ½ □ $V^2$
□ = Density of Air (slugs/ft$^3$)
V = Air Velocity (ft/sec)

thus: **D = [Drag Area] q**

# Aerodynamic Drag of Train = $(½ □ V^2)\, C_d\, A$

Where ρ = air density, V = Train Speed, $C_d$ = Drag Coefficient, and A = Frontal Area



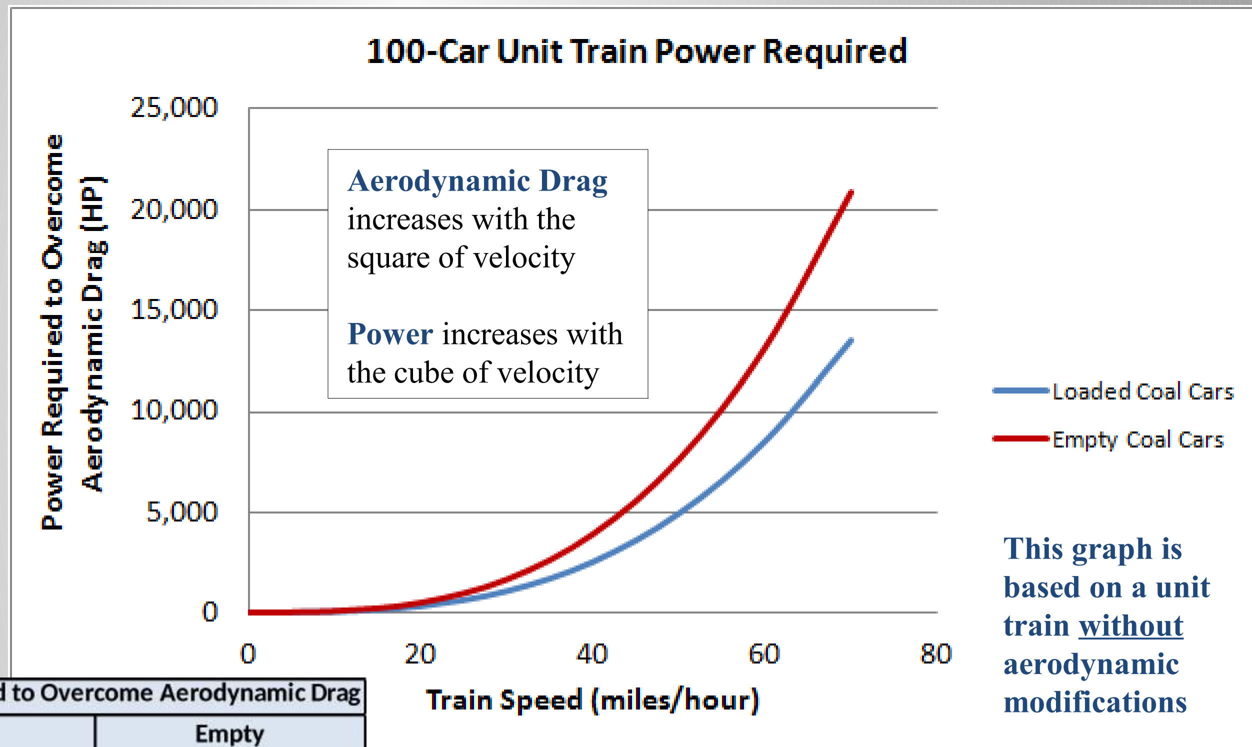

| Train Speed (miles/hour) | Train Speed (ft/sec) | Dynamic Pressure (lb/ft$^2$) | Aerodynamic Drag of Train: Loaded (lbs) | Aerodynamic Drag of Train: Empty (lbs) |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 10 | 14.7 | 0.26 | 1,479 | 2,287 |
| 20 | 29.3 | 1.02 | 5,914 | 9,147 |
| 30 | 44.0 | 2.30 | 13,308 | 20,582 |
| 40 | 58.7 | 4.09 | 23,658 | 36,589 |
| 50 | 73.3 | 6.39 | 36,965 | 57,171 |
| 60 | 88.0 | 9.21 | 53,230 | 82,326 |
| 70 | 102.7 | 12.53 | 72,452 | 112,055 |

Aerodynamic drag at 60 miles/hour is 2.25 times greater than aerodynamic drag at 40 miles/hour.

# Coal Car Aerodynamics: Ranking of Coal Aerodynamic Devices

## Power Required to Overcome Aerodynamic Drag = $(\frac{1}{2}\ \square\ V^2)\ C_d\ A\ V$

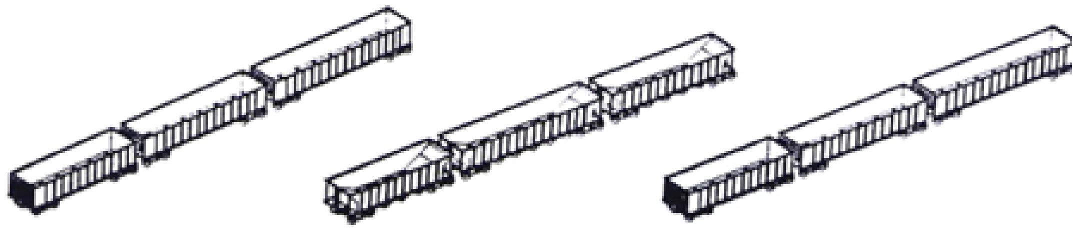
Where V = Train Speed

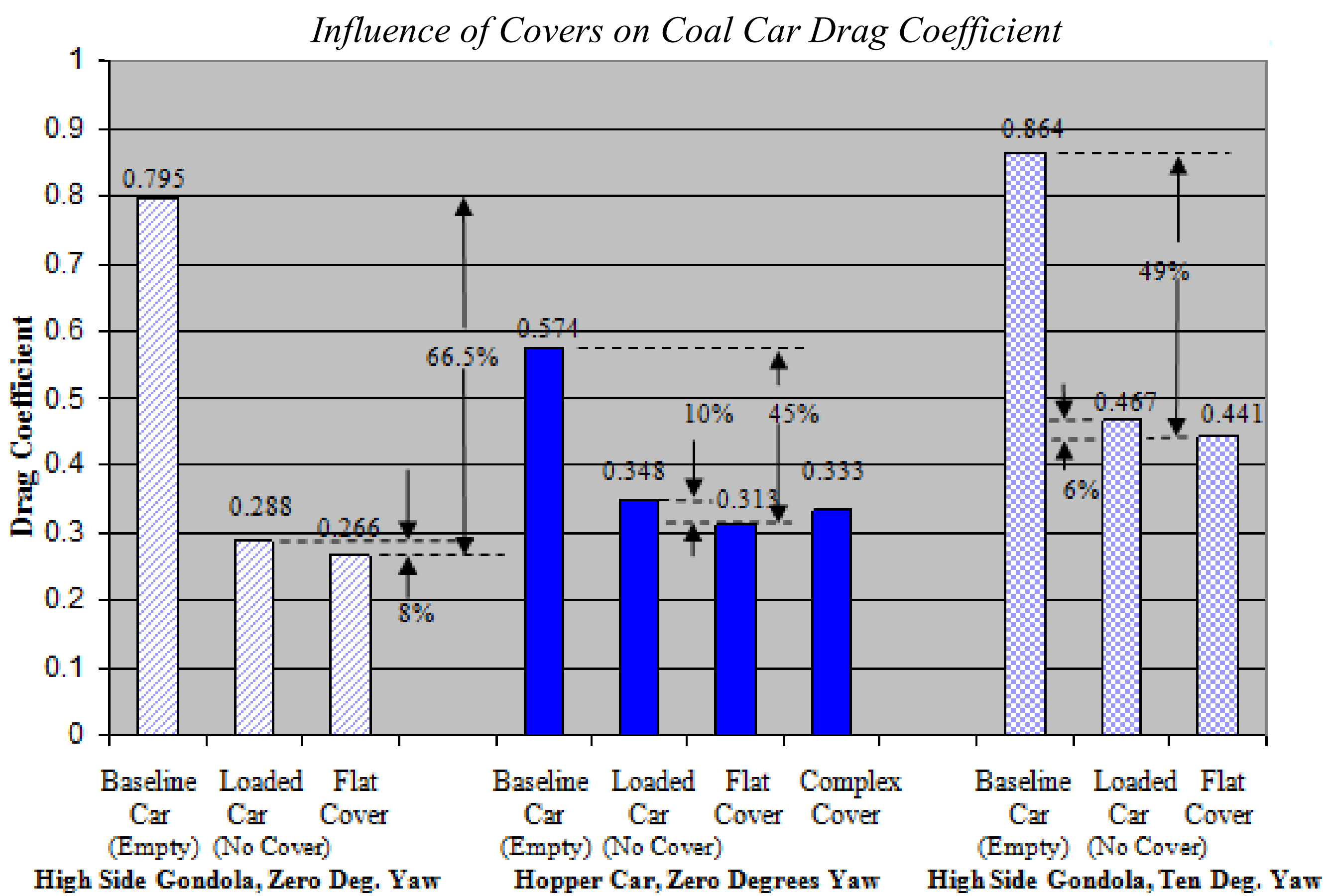



| Train Speed (miles/hour) | Power Required to Overcome Aerodynamic Drag Loaded (lbs) | Empty (lbs) |
|---|---|---|
| 0 | - | - |
| 10 | 39 | 61 |
| 20 | 315 | 488 |
| 30 | 1,065 | 1,647 |
| 40 | 2,524 | 3,903 |
| 50 | 4,929 | 7,623 |
| 60 | 8,517 | 13,172 |
| 70 | 13,524 | 20,917 |

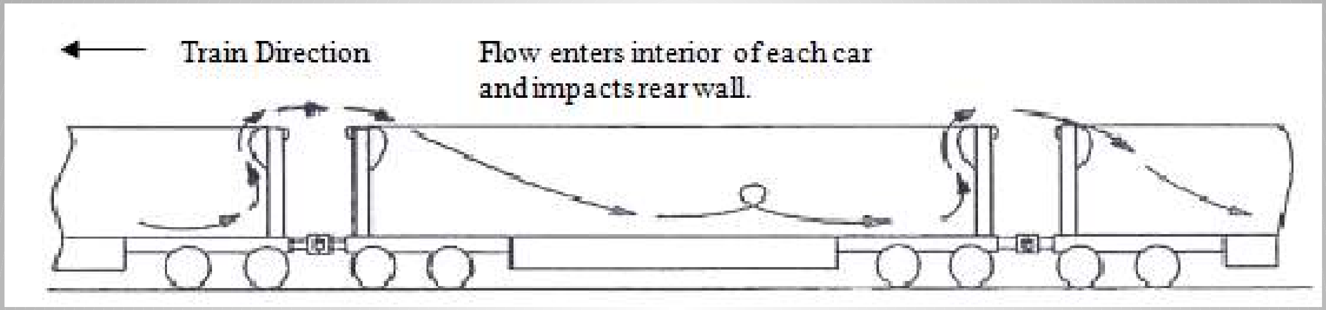
Power required at 60 miles/hour is 3.4 times greater than power required at 40 miles/hour.

# Coal Car Aerodynamics: Covers

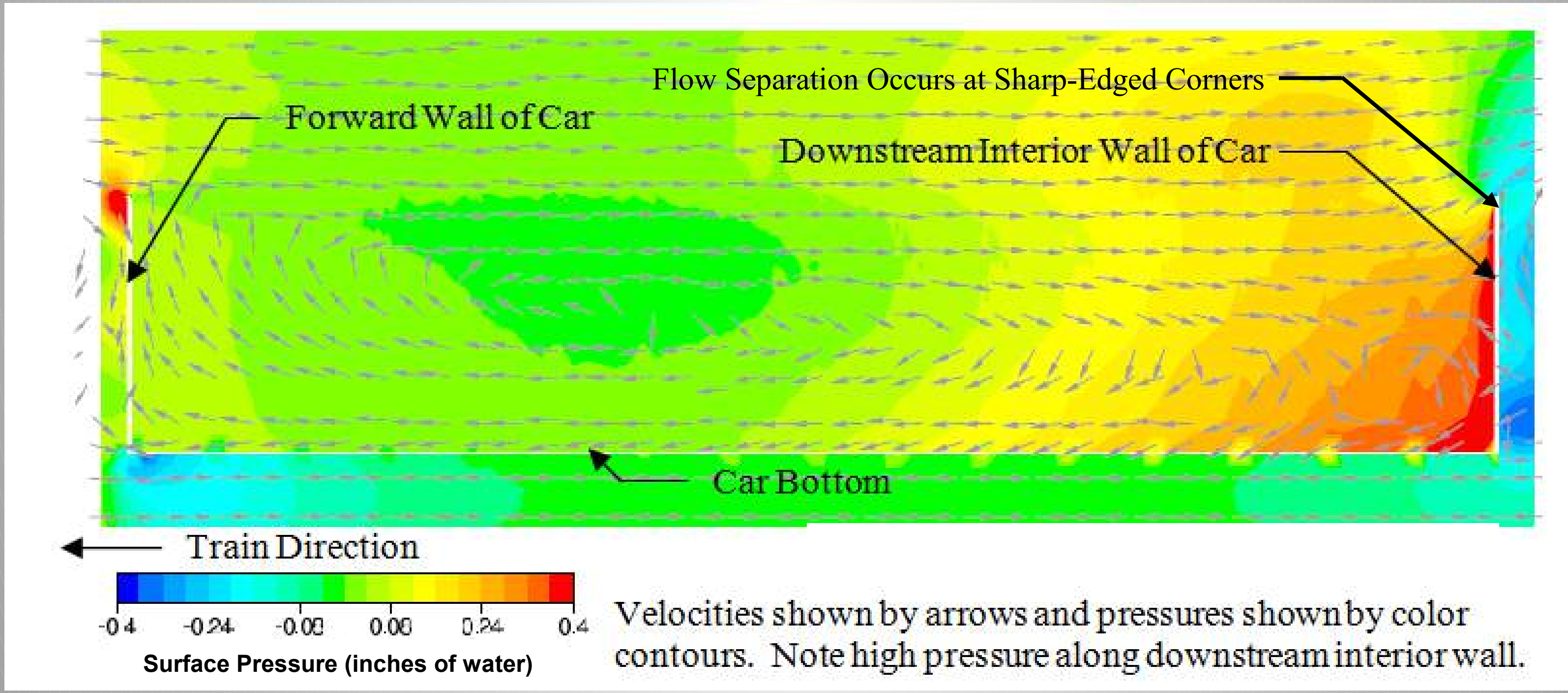




# Coal Car Aerodynamics: Internal Baffles

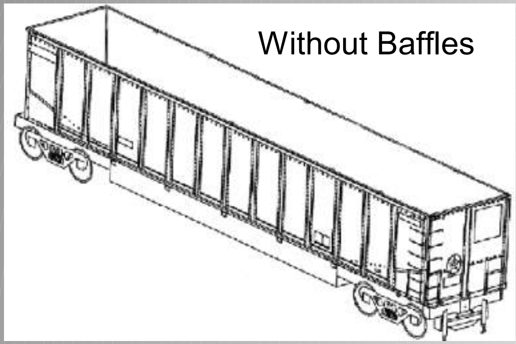


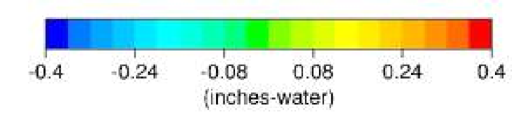

*Observed Flow Behavior in Vicinity of Open-Top Rail Cars*



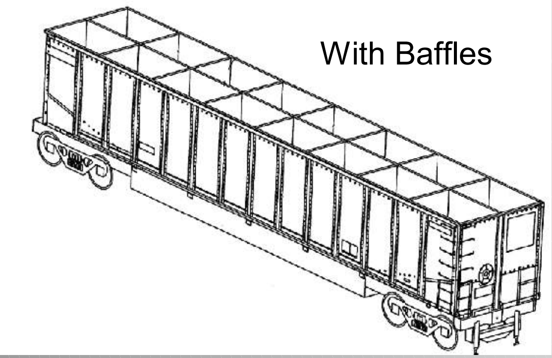

*Calculated Flows and Pressures Along Car Centerline*

# Coal Car Aerodynamics: Internal Baffles

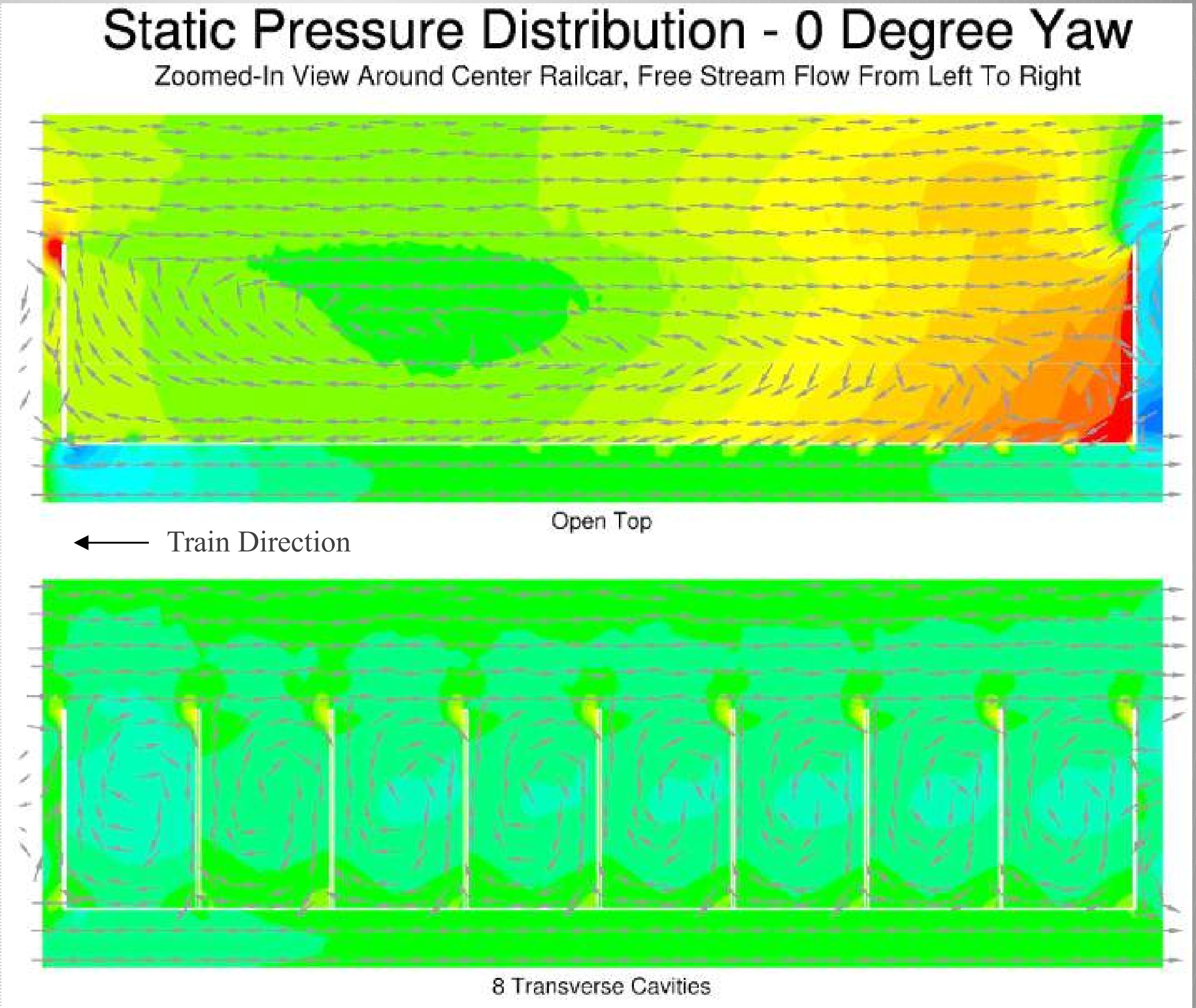



*Static Pressure*

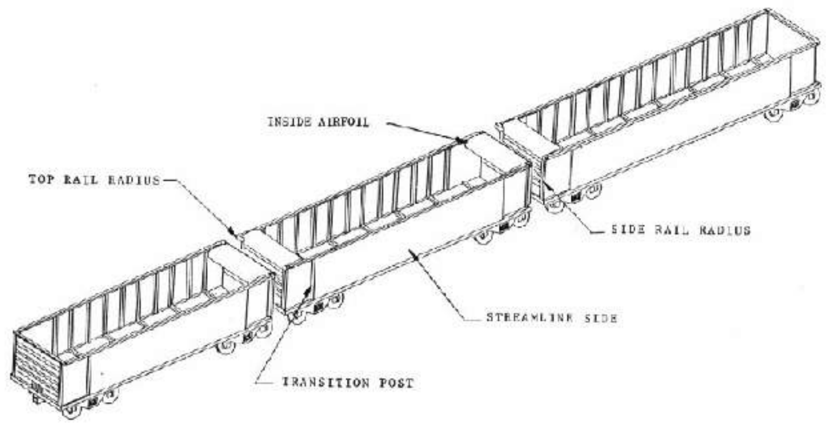



Baffles prevent high velocity air from entering car interior.

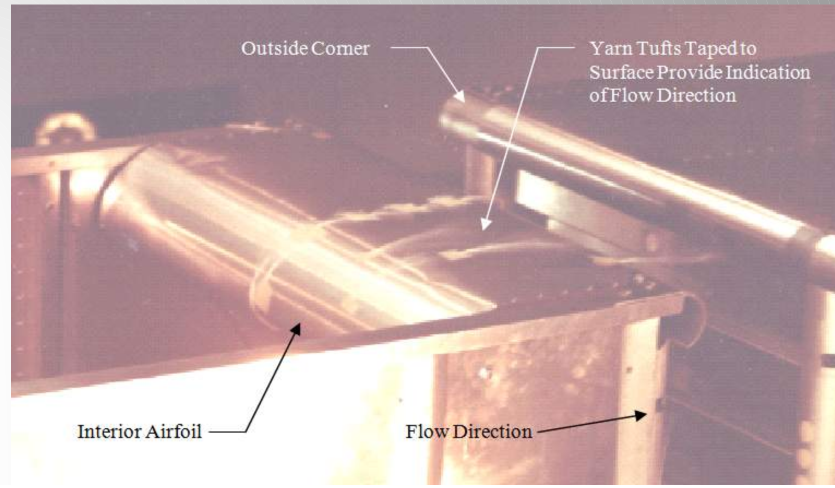



*Car Centerline Velocities and Pressures (with and without baffles); from 3-D CFD Model.*

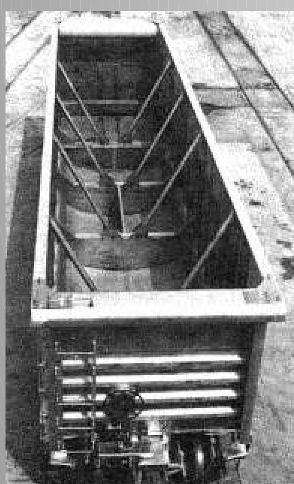
# Coal Car Aerodynamics: End Treatments




*Gondola Car End Treatments*




*Wind Tunnel Test of Airfoils*



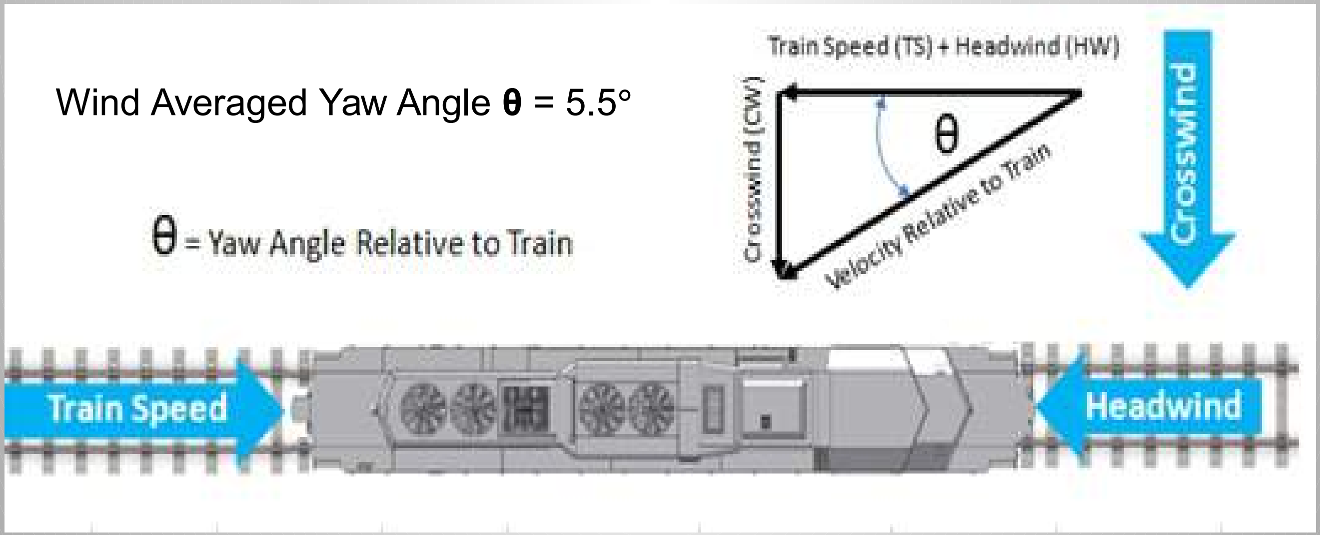
*End Treatments on Pullman Standard Pegasus Car*

*End Treatments on 30% Scale Wind Tunnel Model*

- Adding fairings to the tops of the vertical end walls has been shown to reduce aerodynamic drag of empty cars from 16% to 20%.
- The level of drag reduction depends upon the sophistication of the add-on designs.

## Wind-Average Yaw Angle:

- To rank the effectiveness of the drag reducing devices, the concept of **Wind-Averaged Drag (WAD)** Coefficient is introduced.
- The wind-averaged drag coefficient represents a typical yaw angle based on average wind speeds and train routes in North America. It is defined in SAE Publication J1252.
- The average North American train speed is 43 miles/hour (70 km/hr). The average North American wind speed is 6.8 miles/hour (11 km/hr).
- This produces a wind averaged yaw angle of between 5º and 6º from which the wind-averaged drag value can be determined.



| Drag Reduction Method | Wind-Averaged Drag Area Reduction ($ft^2$) | Wind-Averaged Drag Area Reduction (%) |
|---|---|---|
| **Empty Hopper Cars** | | |
| 1. Flat Covers | 39.3 | 51.7% |
| 2. Full-Height Baffles | 34.3 | 45.1% |
| 3. Smooth Sides | 20.8 | 27.4% |
| 4. Partial Covers (open center) | 18.2 | 23.9% |
| 5. Triangular Baffles | 15.9 | 20.9% |
| 6. Domed Covers | 15.8 | 20.8% |
| 7. End Treatments | 12.8 | 16.8% |
| 8. Rib Caps/Aerodynamic Ribs | 8.1 | 10.7% |
| 9. Effective Gap less than 10 inches | 7.0 | 9.2% |
| 10. Cross Bracing | 6.7 | 8.8% |
| 11. End Enclosure | 5.3 | 7.0% |
| 12. Side Skirts | 4.1 | 5.4% |
| **Empty Gondola Cars** | | |
| 1. Flat Covers | 38.2 | 44.1% |
| 2. Full-Height Baffles | 35.1 | 40.5% |
| 3. Triangular Baffles | 21.7 | 25.1% |
| 4. Domed Covers | 19.3 | 22.3% |
| 5. Partial Covers (open center) | 17.7 | 20.4% |
| 6. End Treatments | 17.2 | 19.9% |
| 7. Smooth Sides | 13.4 | 15.5% |
| 8. Cross Bracing | 8.2 | 9.5% |
| 9. Rib Caps/Aerodynamic Ribs | 7.5 | 8.7% |
| 10. Effective Gap less than 10 inches | 6.0 | 6.9% |
| 11. Side Skirts | 4.1 | 4.7% |

Effectiveness of Aerodynamic Drag Modifications on Coal Car Wind-Averaged Drag

- Coal Car Aerodynamics
- **Impact of Candidate Aerodynamic Devices on Train Fuel Economy**
- Conclusions and Recommendations

*BNSF Unit Coal Train Leaving Powder River Basin, Wyoming*

## Energy and Fuel Usage Calculations
## (Spread-Sheet Method)

If *F(x)* = total resistance force acting on train, the energy required to overcome this force is given by the following formula:

$$Energy\ Required = E = \int_0^L F(x)dx$$

To determine the energy required for a given train journey, we divide the track into segments and determine the forces acting along each segment:

$$E \approx \sum_{i=0}^{i=N} F_i X_i \quad where\ i = trip\ segment\ and\ F_i\ are\ the\ forces\ acting\ over\ segment\ X_i$$

## Calculations Based on Fuel Usage Spread-Sheet Method:

Components of Resistive Force Acting on Train:

- Gravity (Elevation Changes)
- Rolling Resistance (Including Journal Bearings)
- Acceleration (F = ma) for starting and speed changes
- Flange Resistance (Curves)
- Aerodynamic Drag

***High Speed Unit Train***

a. From Mine to Power Plant

| Resistance Force | | | Energy Expended (ft-lbs) | (BTU) | (MJ) | % of Total |
|---|---|---|---|---|---|---|
| Elevation Changes | | | 0.0000E+00 | 0.0000E+00 | 0 | 0.00 |
| Rolling Resistance | | | 2.0094E+11 | 2.5841E+08 | 272,437 | 53.16 |
| Acceleration: | Starting Resistance | | 2.9719E+09 | 3.8219E+06 | 4,029 | 0.79 |
| | Speed Changes | | 3.2860E+10 | 4.2258E+07 | 44,552 | 8.69 |
| Flange Resistance (Curves) | | | 5.0743E+09 | 6.5255E+06 | 6,880 | 1.34 |
| Aerodynamic Drag | | | 1.3613E+11 | 1.7506E+08 | 184,564 | 36.02 |
| | | Totals: | 3.7798E+11 | 4.8608E+08 | 512,461 | |

b. From Power Plant to Mine

| Resistance Force | | | Energy Expended (ft-lbs) | (BTU) | (MJ) | % of Total |
|---|---|---|---|---|---|---|
| Elevation Changes | | | 1.5036E+10 | 1.9336E+07 | 20,385 | 5.17 |
| Rolling Resistance | | | 5.4897E+10 | 7.0597E+07 | 74,429 | 18.87 |
| Acceleration: | Starting Resistance | | 4.0596E+08 | 5.2207E+05 | 550 | 0.14 |
| | Speed Changes | | 8.9773E+09 | 1.1545E+07 | 12,171 | 3.09 |
| Flange Resistance (Curves) | | | 1.3863E+09 | 1.7828E+06 | 1,880 | 0.48 |
| Aerodynamic Drag | | | 2.1029E+11 | 2.7044E+08 | 285,118 | 72.27 |
| | | Totals: | 2.9100E+11 | 3.7422E+08 | 394,534 | |

*Typical Energy Model Calculation Summary*

# Calculations Based on Fuel Usage Spread-Sheet Method:

Aero Transportation Products
ASC Project AT0: Train Fuel Usage Spreadsheet

**Airflow Sciences Corporation**
12190 Hubbard Street
Livonia, MI 48150-1737
Tel.: 734-525-0300, Fax: 734-525-0303
Web: www.airflowsciences.com

Input Variables are Highlighted in Yellow (suggested baseline values are indicated for each variable)

**Title:** Example Energy and Economics Model Input
**Date:**

| Variable | Enter Value | Suggested Baseline Value | Variable | Enter Value | Suggested Baseline Value | Variable | Enter Value | Suggested Baseline Value |
|---|---|---|---|---|---|---|---|---|
| **Locomotives** | | | | | | | | |
| Number of Locomotives | 4 | 4 | Locomotive Make and Model | GE C44-9W | GE C44-9W | Engine Power (HP) | 4,400 | 4,400 |
| Fuel Tank Capacity (gallons) | 5,000 | 5,000 | Engine Model | FDL-16 | FDL-16 | Generator Efficiency (%) | 94 | 94 |
| Locomotive Dry Weight (lbs) | 394,000 | 394,000 | Engine Thermal Efficiency (%) | 33 | 33 | Traction Motor Efficiency (%) | 90 | 90 |
| Locomotive Weight with Full Fuel Tank (lbs) | 429,450 | 429,450 | Locomotive Drag Area (ft$^2$) at 5.5 degrees yaw angle | 118.6 | 118.6 | Propulsion System Efficiency (%) (engine efficiency x generator efficiency x motor efficiency) | | 27.9 |
| **Coal Cars** | | | | | | | | |
| Number of Coal Cars in Train | 100 | 100 | Coal Car Empty Weight (lbs) | 58,000 | 58,000 | Baseline Drag Area (ft$^2$) at 5.5 degrees yaw angle* | Loaded | 55.0 |
| Coal Car Type | Gondola | | Coal Car Loaded Weight (lbs) | 258,000 | 258,000 | | Empty | 86.6 |
| Aerodynamic Modification: | None (Baseline) | | | | | Drag Area Reduction (ft$^2$) at 5.5 degrees yaw angle | Loaded | 0 |
| Per Car Weight Change Due to Aerodynamic Modification (negative: car weight decreases; positive: car weight increases) (lbs) | | | | | 0 | | Empty | 0 |
| **Route** | | | | | | | | |
| Distance Mine to Power Plant (miles) | 922 | 922 | Number of Starts from Full Stop | 4 | 4 | Number of Curves per Mile | 0.5 | |
| Elevation Change Mine to Power Plant (ft) | | | Average Ambient Temperature (°F) | 50 | 50 | Average Curvature (degrees) | 5 | |
| (enter positive or negative value) | -2,000 | | Rolling Resistance Coefficient | 0.0015 | 0.0015 | | | |
| **Economic Input** | | | | | | | | |
| Freight Through Rate (per net delivered ton) | $14.00 | $14.00 | Diesel Fuel Cost (per gallon) | $2.18 | $2.18 | Number of Round Trips per Year per Car | | 35.0 |

*Baseline Drag Areas for Locomotives and Coal Cars: these are drag areas at 5.5° yaw (wind averaged drag area):

| Car Type | Wind Averaged Drag Area (ft$^2$) | Reference |
|---|---|---|
| Locomotive: EMD | 111.1 | AAR R-685, Page 146 |
| GE | 118.6 | AAR R-685, Page 151 |
| Coal Cars: Loaded Hopper | 49.2 | ASC R-08-ATP-3, Page 112 |
| Empty Hopper | 76.0 | ASC R-08-ATP-3, Page 112 |
| Loaded Gondola | 55.0 | ASC R-08-ATP-3, Page 112 |
| Empty Gondola | 86.6 | ASC R-08-ATP-3, Page 112 |

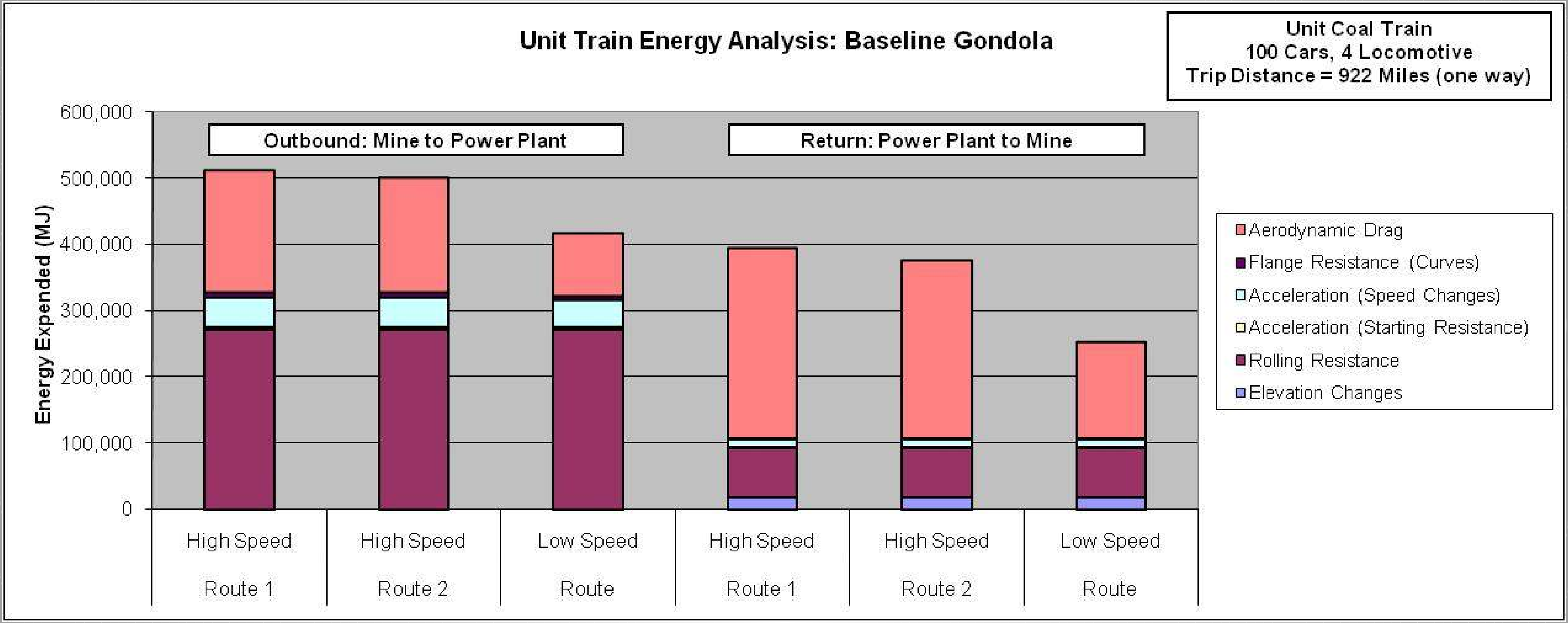
Locomotive Position-In-Train Drag Area Factors:
(drag changes with position in train)

| Position (1 = front) | Drag Area Factor |
|---|---|
| 1 | 1.00 |
| 2 | 0.60 |
| 3 | 0.49 |
| 4 | 0.44 |

Density of Diesel Fuel: 7.09 lbs/gallon

*Train Energy and Economics Model Input Parameters*

## Calculations Based on Fuel Usage Spread-Sheet Method:




For these examples the energy required to transport the empty coal cars back to the mine requires between 60% and 80% of the energy required to transport the loaded cars from the mine to the power plant.

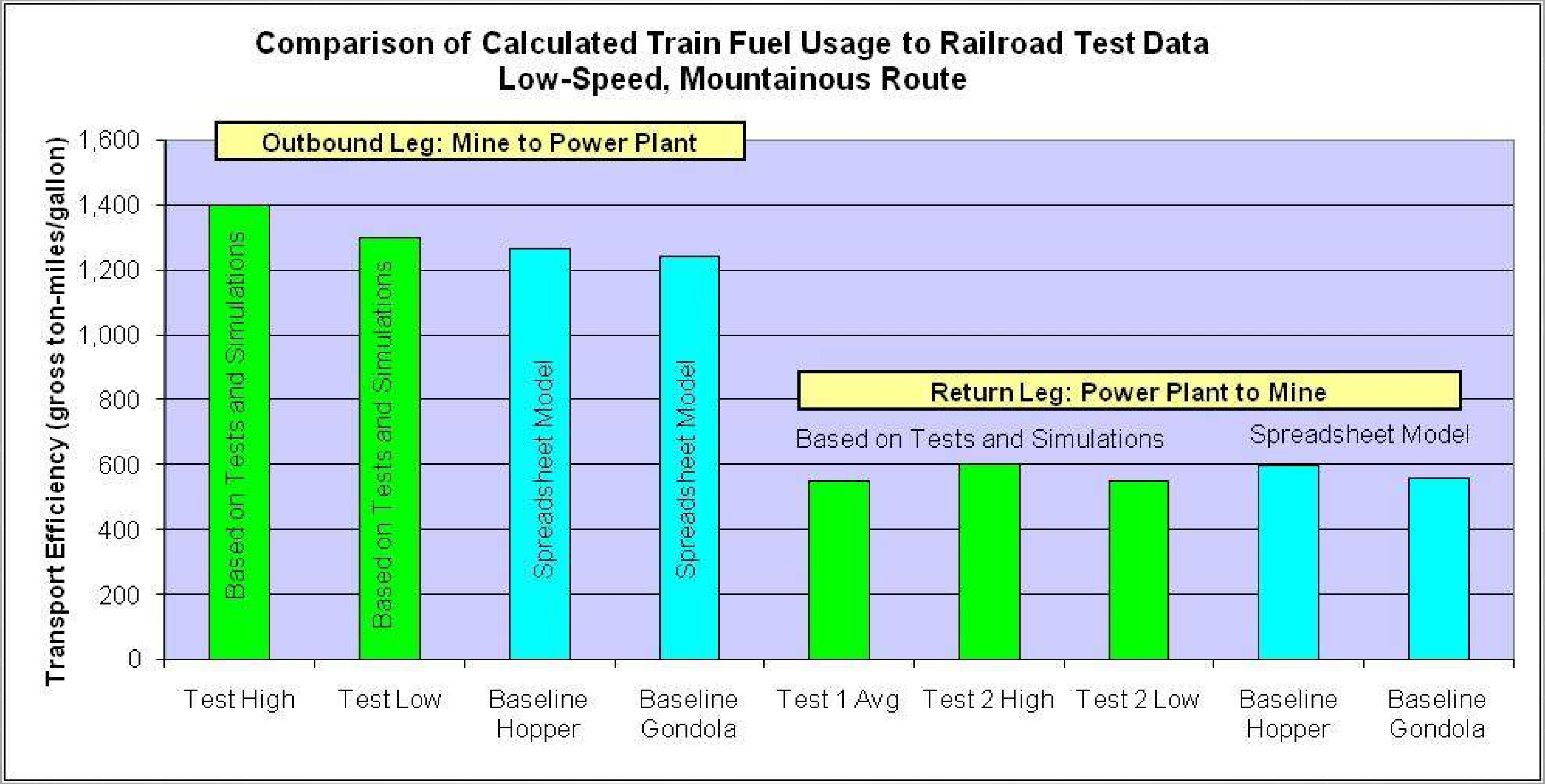
## Calculations Based on Energy and Fuel Usage Model:

| | | | | |
|---|---|---|---|---|
| Freight Through Rate (per net delivered ton) | $14.00 | Diesel Fuel Cost (per gallon) | $2.18 | |
| **High Speed Route 1** | | | | |
| Locomotive Propulsion System Efficiency | 11.33 | kilowatt-hours/gallon | Energy Expended (Mine to Power Plant kilowatt-hours) | 142,324 |
| Gross Train Weight x Distance (outbound) | 12,685,706 | gross ton-miles Mine to Power Plant | Energy Expended (Power Plant to Mine kilowatt-hours) | 109,572 |
| Gross Train Weight x Distance (return) | 3,465,706 | gross ton-miles Power Plant to Mine | Number of Round Trips per Year per Coal Car | 35 |
| Fuel Consumed (outbound) | 12,560 | gallons Mine to Power Plant | Transport Efficiency Outbound (gross ton-miles/gallon) | 1,010 |
| Fuel Consumed (return) | 9,670 | gallons Power Plant to Mine | Transport Efficiency Return (gross ton-miles/gallon) | 358 |
| Total Fuel Consumed (round trip) | 22,231 | gallons Round Trip | Transport Efficiency Round Trip (gross ton-miles/gallon) | 727 |
| Gross Train Weight x Distance (round trip) | 16,151,412 | gross ton-miles Round Trip | Fuel Used Per Car Per Year (gallons) | 7,781 |
| **Low Speed Mountainous Route** | | | | |
| Locomotive Propulsion System Efficiency | 11.33 | kilowatt-hours/gallon | Energy Expended (Mine to Power Plant kilowatt-hours) | 115,921 |
| Gross Train Weight x Distance (outbound) | 12,685,706 | gross ton-miles Mine to Power Plant | Energy Expended (Power Plant to Mine kilowatt-hours) | 70,281 |
| Gross Train Weight x Distance (return) | 3,465,706 | gross ton-miles Power Plant to Mine | Number of Round Trips per Year per Coal Car | 35 |
| Fuel Consumed (outbound) | 10,230 | gallons Mine to Power Plant | Transport Efficiency Outbound (gross ton-miles/gallon) | 1,240 |
| Fuel Consumed (return) | 6,202 | gallons Power Plant to Mine | Transport Efficiency Return (gross ton-miles/gallon) | 559 |
| Total Fuel Consumed (round trip) | 16,433 | gallons Round Trip | Transport Efficiency Round Trip (gross ton-miles/gallon) | 983 |
| Gross Train Weight x Distance (round trip) | 16,151,412 | gross ton-miles Round Trip | Fuel Used Per Car Per Year (gallons) | 5,751 |
| **High Speed Route 2** | | | | |
| Locomotive Propulsion System Efficiency | 11.33 | kilowatt-hours/gallon | Energy Expended (Mine to Power Plant kilowatt-hours) | 139,196 |
| Gross Train Weight x Distance (outbound) | 12,685,706 | gross ton-miles Mine to Power Plant | Energy Expended (Power Plant to Mine kilowatt-hours) | 104,784 |
| Gross Train Weight x Distance (return) | 3,465,706 | gross ton-miles Power Plant to Mine | Number of Round Trips per Year per Coal Car | 35 |
| Fuel Consumed (outbound) | 12,284 | gallons Mine to Power Plant | Transport Efficiency Outbound (gross ton-miles/gallon) | 1,033 |
| Fuel Consumed (return) | 9,248 | gallons Power Plant to Mine | Transport Efficiency Return (gross ton-miles/gallon) | 375 |
| Total Fuel Consumed (round trip) | 21,532 | gallons Round Trip | Transport Efficiency Round Trip (gross ton-miles/gallon) | 750 |
| Gross Train Weight x Distance (round trip) | 16,151,412 | gross ton-miles Round Trip | Fuel Used Per Car Per Year (gallons) | 7,536 |

*Example Output File: Energy Section of Train Energy and Economics Model (Baseline Gondola)*

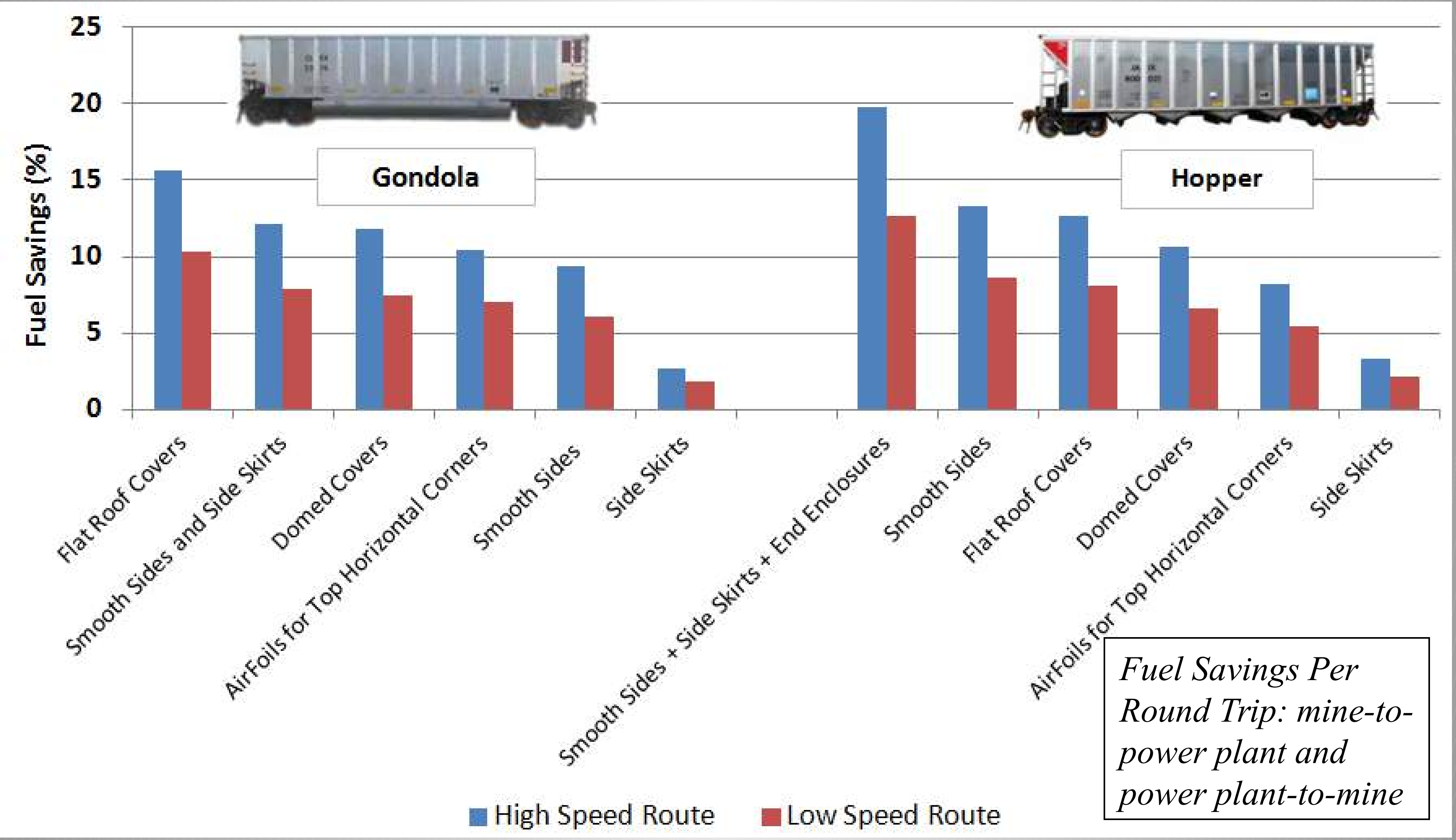
## Fuel Usage Calculations:

### Comparison of Fuel Measurements to Results of Energy Simulation



## Calculations Based on Fuel Usage Spread-Sheet Method:

*Example Output: Economics Section of Train Energy and Economics Model*




Assumptions: Diesel Fuel Cost: $3.02/gallon Freight Through Rate: $18.00/net delivered ton mile Number of Trips per Year per Car: 35

## Calculation of ROI for Retrofit Aerodynamic Devices:

To determine the **return on investment (ROI)** associated with the candidate retrofit aerodynamic devices, the following procedure was followed:

Calculate the **fuel savings associated with each device** using the spread-sheet-based calculation procedure. Multiply by the fuel cost to obtain the **savings in dollars per car per year.**

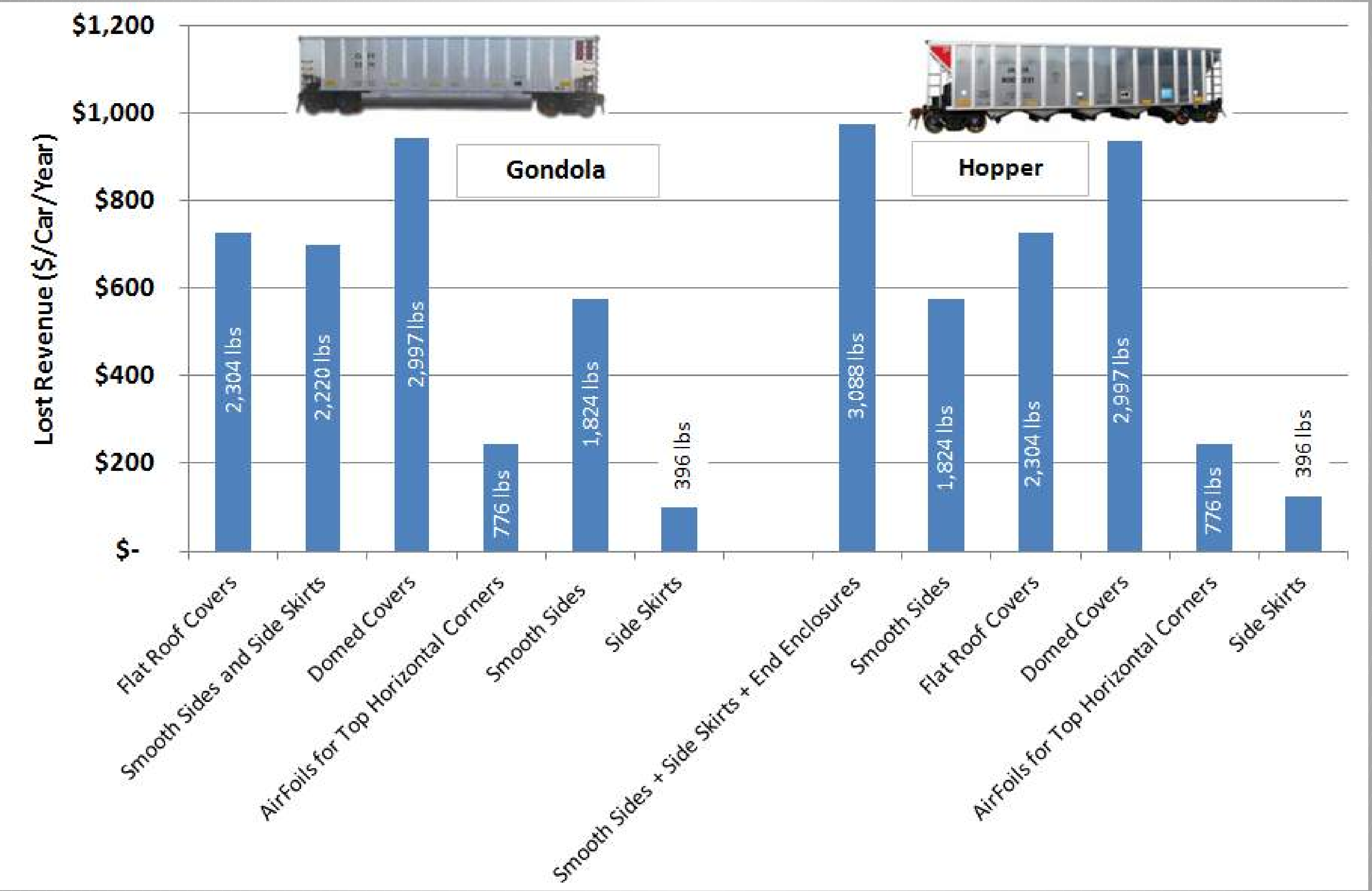
↓

**Subtract the lost revenue** (due to displaced payload) associated with the weights of the add-on aerodynamic devices to **obtain the Net Cost Reduction** (dollars per car per year).

↓

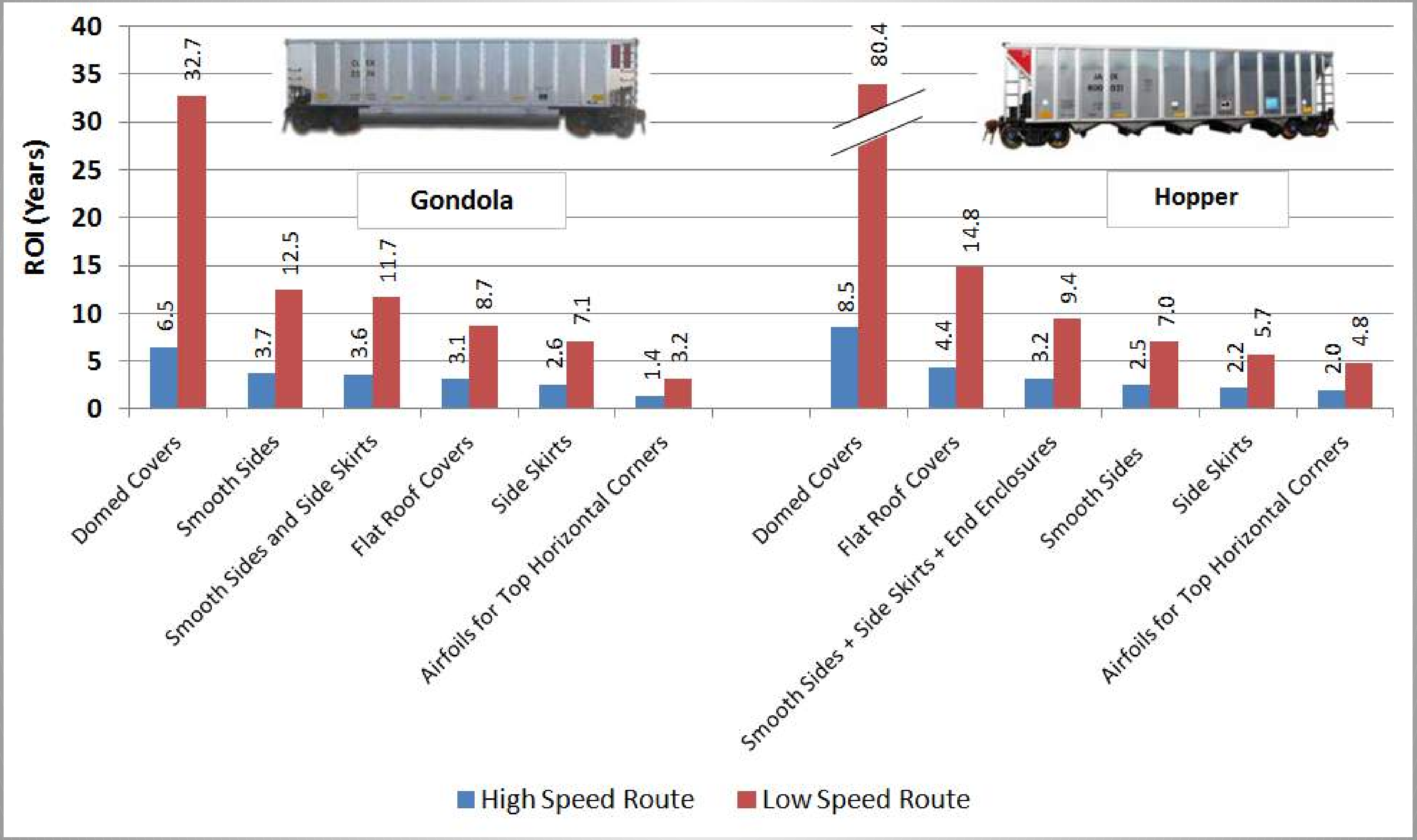
**Divide** the cost of the retrofit aerodynamic device (dollars per car) **by the Net Cost Reduction to obtain the ROI (years).**

## Lost Revenue due to Weight of Retrofit Aerodynamic Devices:




Assumptions: Freight Through Rate: $18.00/net delivered ton mile
Number of Trips per Year per Car: 35

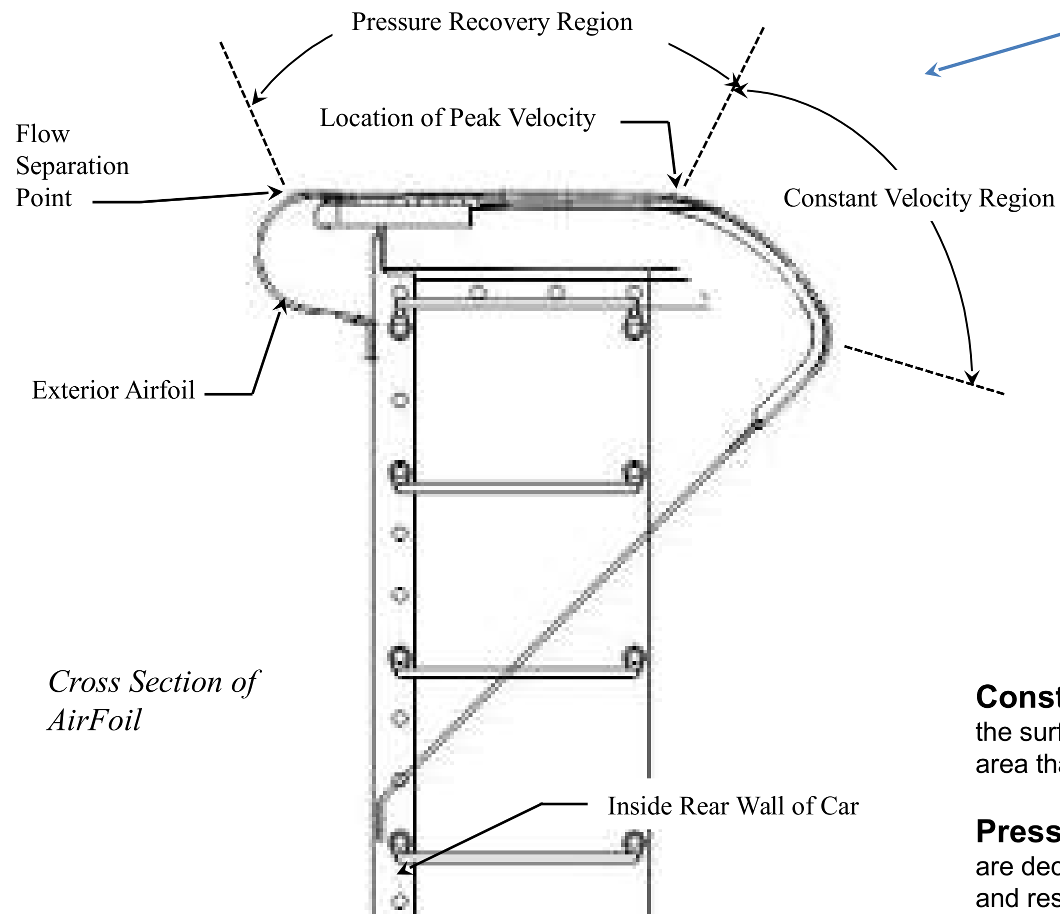
## Calculation of ROI for Retrofit Aerodynamic Devices:



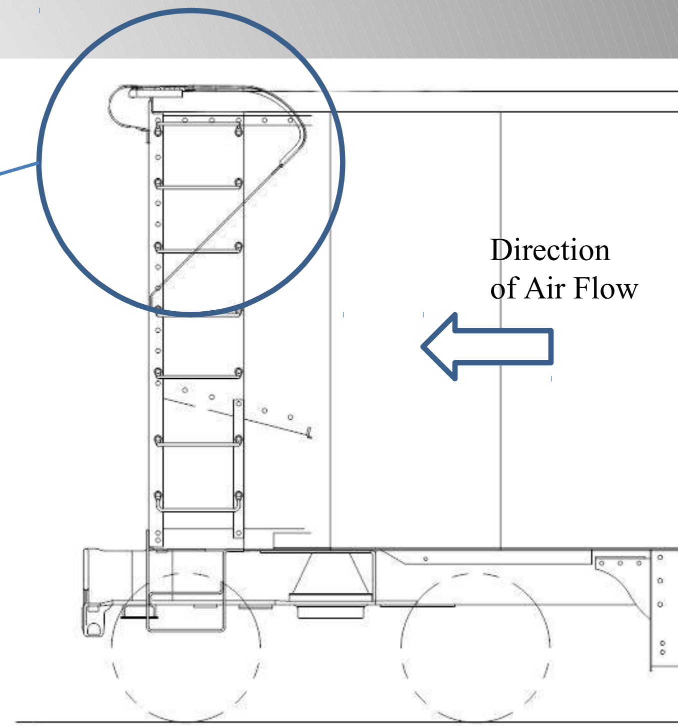



Assumptions: Diesel Fuel Cost: $3.02/gallon Freight Through Rate: $18.00/net delivered ton mile Number of Trips per Year per Car: 35

## Aerodynamic Design of AirFoils




*Cross Section of AirFoil*




**Constant Velocity Region:** In this region, velocities along the surface are higher than freestream, creating a low pressure area that produces a force acting in the direction of travel.

**Pressure Recovery Area:** In this region, the air velocities are decreased in a controlled manner to prevent flow separation and resulting energy loss.

*The AirFoil geometry was developed using computational fluid dynamics modeling and boundary layer separation theory.*

## Power Reduction due to Addition of AirFoils

| Coal Car Configuration | Train Speed (miles/hour) | Power Required (HP) | Power Reduction Due to Addition of AirFoils |
|---|---|---|---|
| Without AirFoils | 40 | 4,855 | |
| | 60 | 14,076 | |
| With AirFoils | 40 | 4,244 | 10% to 13% |
| | 60 | 12,014 | 14% to 15% |

*Impact o* *rack*
*(100 Empty Coal Cars + 4 Locomotives)*

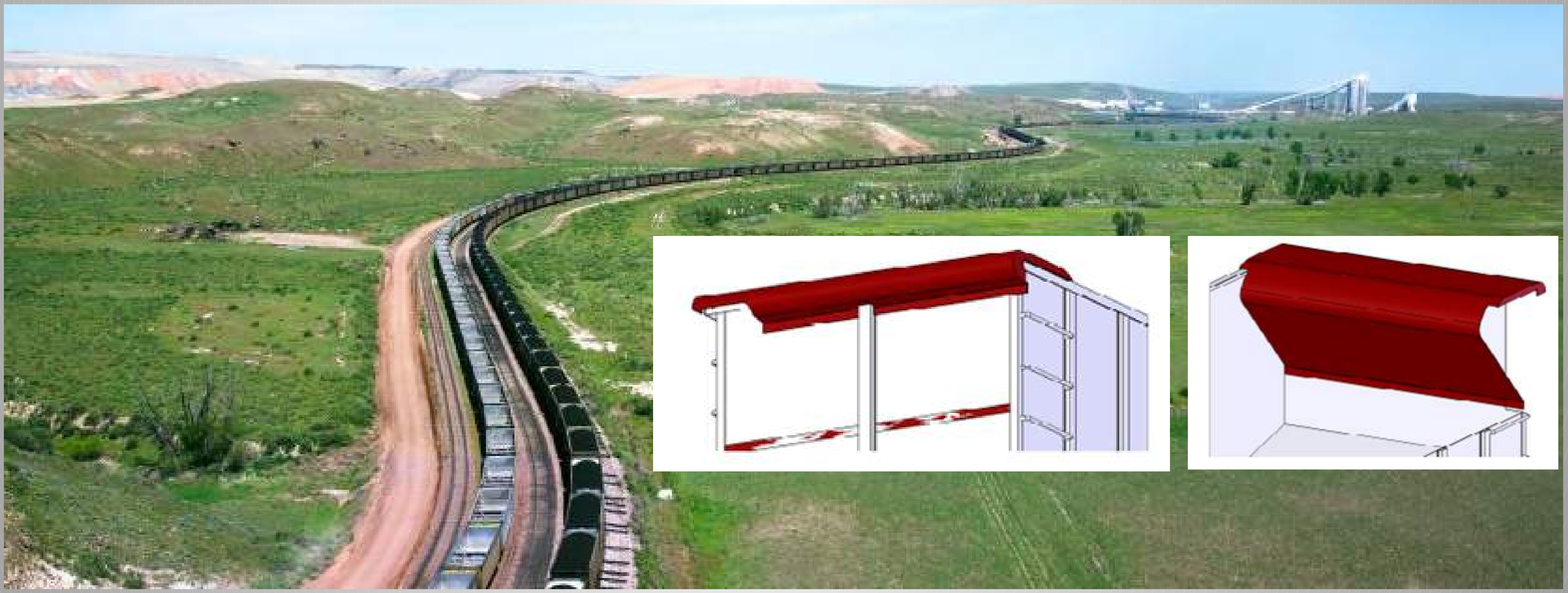
Surface Velocities




Airflow Sciences Corporation

## Impact of AirFoils on Fuel Use: Unit Train Round Trip

- The projected fuel savings for a round trip unit train from coal mine to power plant (loaded cars on outbound leg and empty cars on return leg), varied from 5.4% to 8.1%, depending upon the coal car type, train speed histogram, and coal pile geometry.
- For other car, train speed, and coal pile combinations, most notably, flat-floor gondola cars, the payback period resulting from addition of AirFoils can be as short as 1.4 years.



# AirFoil Durability

## AirFoils do not impede car loading or unloading operations

*AirFoil Durability Testing:*

*In-Service Evaluations; Photos of Car Loading Operation*

Test cars have been in service for over 3 years.

AirFoils do not limit load capacity of cars

- Coal Car Aerodynamics
- Impact of Candidate Aerodynamic Devices on Train Fuel Economy
- **Conclusions and Recommendations**


*AirFoils Exterior (left) and Interior (above) Views*

## Coal Car Aerodynamics: Conclusions

- Aerodynamic drag represents over 70% of the tractive effort required to move an empty unit coal train and over 36% of the tractive effort required to move a loaded unit coal train.
- The energy required to transport the empty coal cars back to the mine requires between 60% and 80% of the energy required to transport the loaded cars from the mine to the power plant.
- Retrofit aerodynamic devices, including covers, baffles, smooth sides, AirFoils, and side skirts, are effective at reducing aerodynamic drag of both loaded and empty coal cars. Aerodynamic drag reductions can be as high as 44% - 50% for covers, and 17% - 20% for AirFoils.

## Coal Car Aerodynamics: Conclusions

- Fuel savings per round trip (mine-to-power plant and power plant-to-mine) resulting from addition of aerodynamic devices ranges from 2% to 20%, depending upon car type and train speed history. Flat covers and combinations of modifications produce the greatest drag reductions.
- Aerodynamic retrofit devices add weight to the car and impact the load capacity. Some devices, for example dome-style covers, can increase car weight by over 1.5 tons.
- The projected fuel savings for a round trip unit train equipped with AirFoils varies from 5.4% to 8.1%, depending upon the coal car type, train speed histogram, and coal pile geometry.

## Coal Car Aerodynamics: Conclusions

- An economic evaluation indicates AirFoils offer the best return on investment for the aerodynamic devices evaluated. Payback periods range from a high of 4.8 years for low-speed routes to 1.4 years for higher speed routes.

- Reducing train fuel use impacts greenhouse gas emissions. Reducing GHG emissions may provide opportunities for carbon credits.

- Based on industry publications, the U.S. transportation of coal requires on the order of 1.5 billion gallons of diesel fuel each year. Thus, a 5% fuel savings would be 75 million gallons, or 2% of all Class I railroad fuel consumption.

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