

Railroad Transportation Energy Efficiency

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Presentation Outline

- Fundamentals of railroad transportation energy efficiency
- Measuring railroad train resistance
- Intermodal train aerodynamics and train resistance
- Optimizing intermodal train loading to minimize resistance
- Use of machine-vision to automatically monitor intermodal train loading efficiency



JEOPARDY!

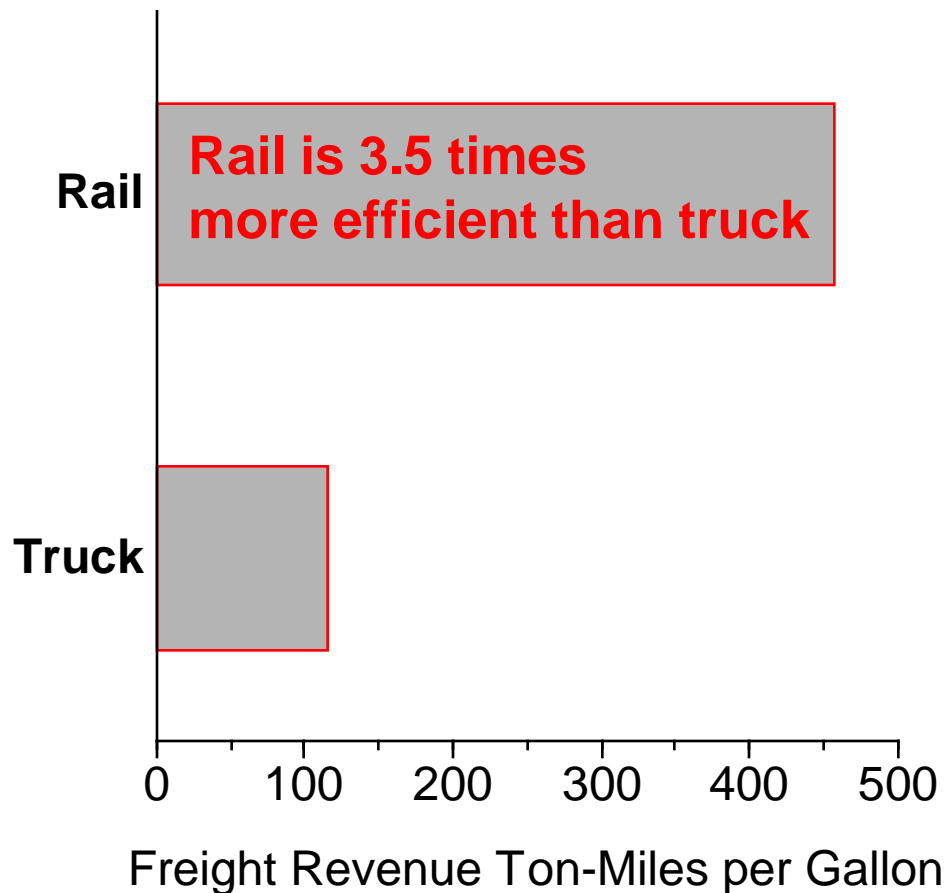
What is
457?



THE NUMBER OF
MILES RAILROADS
CAN MOVE ONE TON
OF FREIGHT ON ONE
GALLON OF FUEL

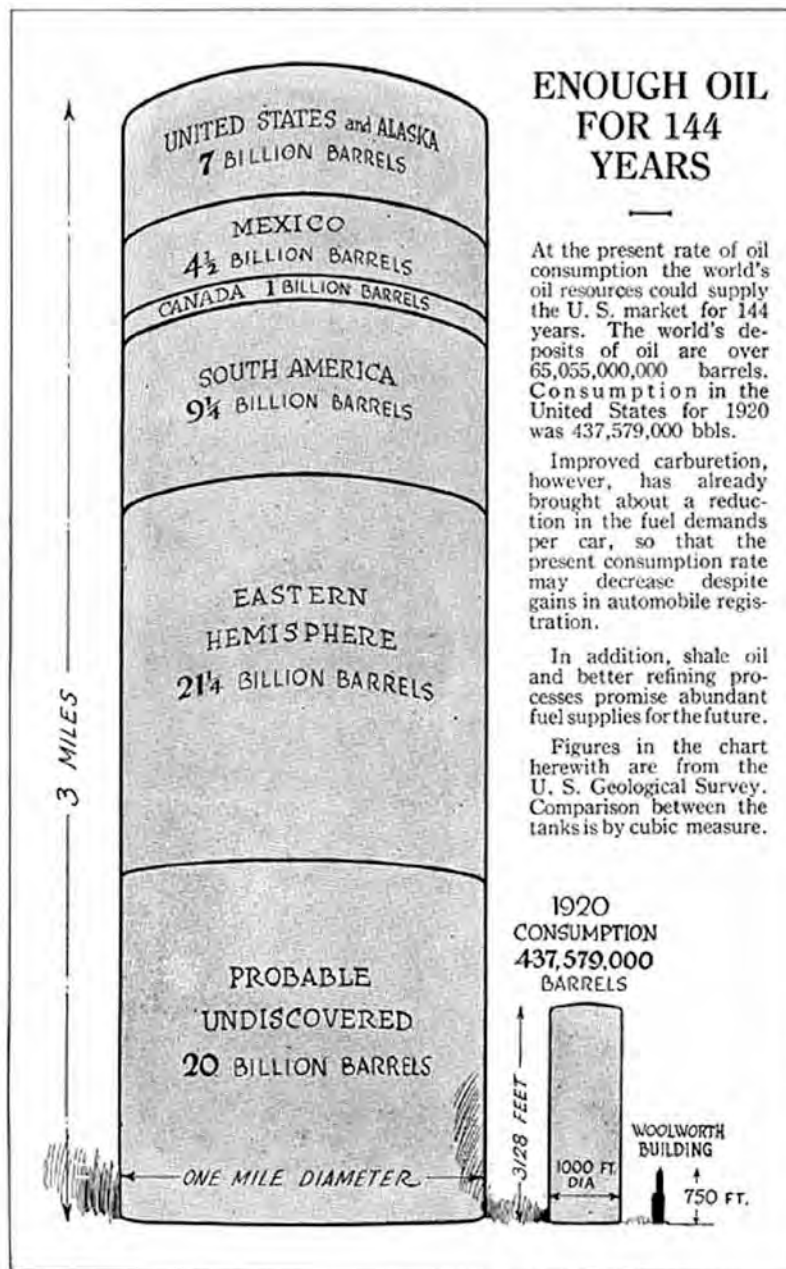
Energy efficiency truck vs. rail

- How does that compare to truck transport?



(AAR & FRA data)





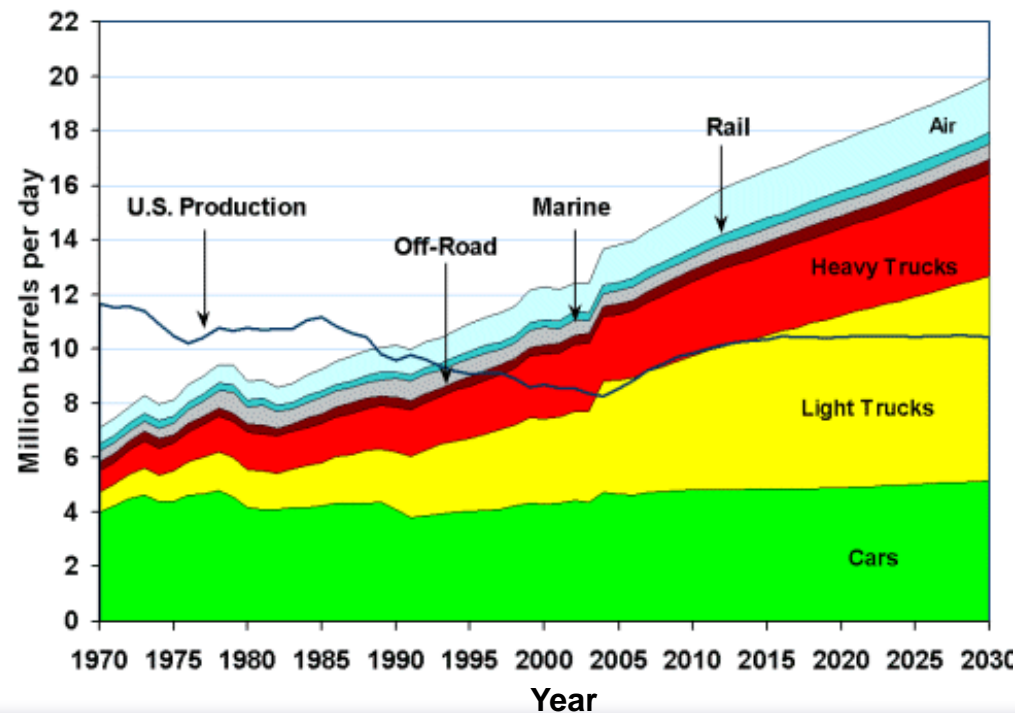
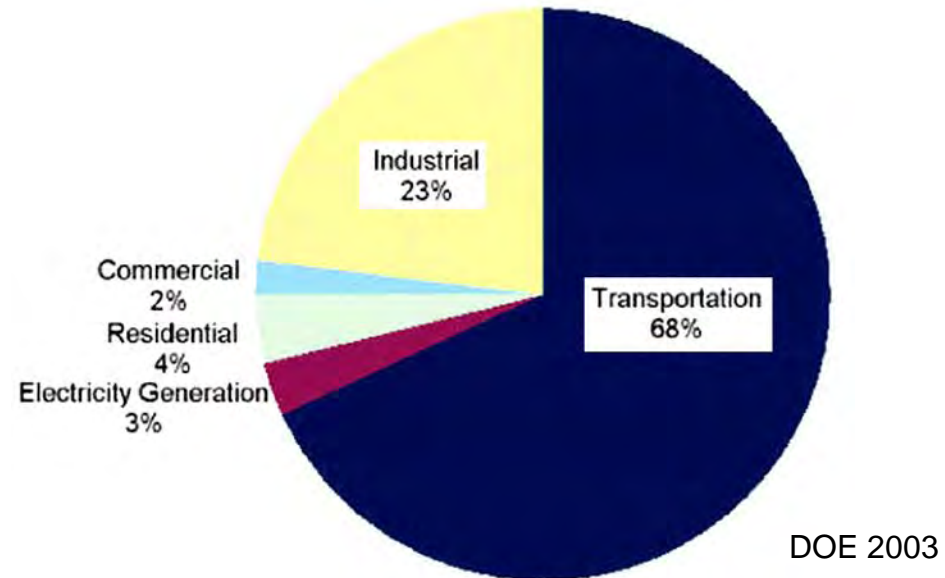
US 20th Century was about **CONVENIENCE**

The 21st must consider
EFFICIENCY as well

- Then
 - Abundant: energy, land, natural resources, labor, dominant economy
- Now
 - *Diminishing resources:*
 - Energy
 - Air quality
 - Water
 - Land
 - *Congestion*
 - Need more efficient use of transportation infrastructure
 - *Stronger global competition*

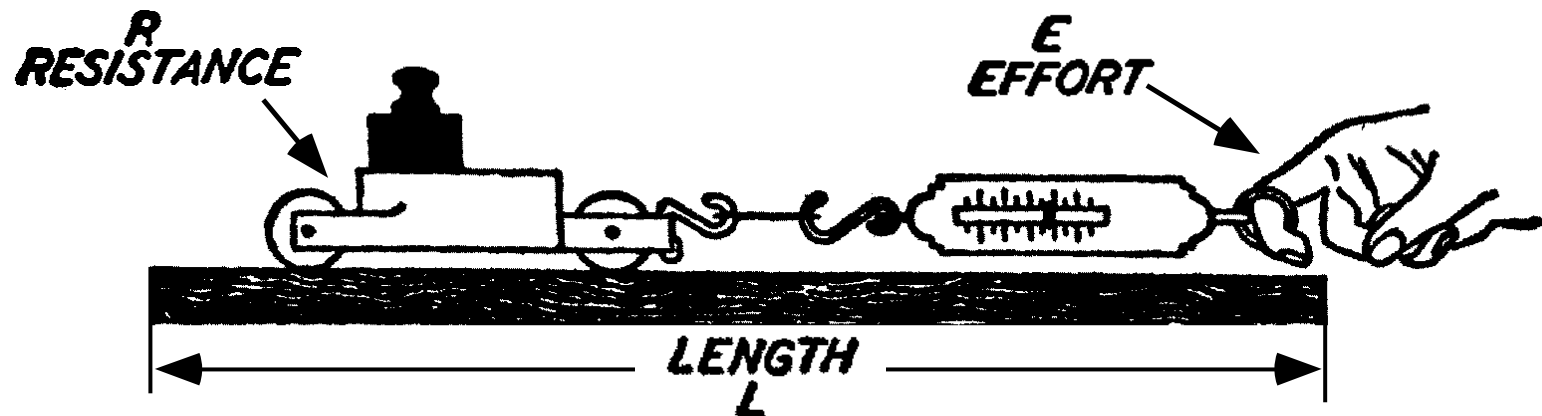
Petroleum-derived energy consumption

- Transportation accounts for the majority of petroleum energy consumption in the U.S.
- Of this cars, light trucks (including SUVs) and heavy trucks account for a large majority, followed by air
- Rail consumes only a small fraction of transportation consumption (estimated to be 2.2% of total in 2009)
- Contrast percentage consumed by rail compared to heavy trucks,
- Recall that rail moves about 42% of intercity freight ton-miles whereas trucks move about 30%

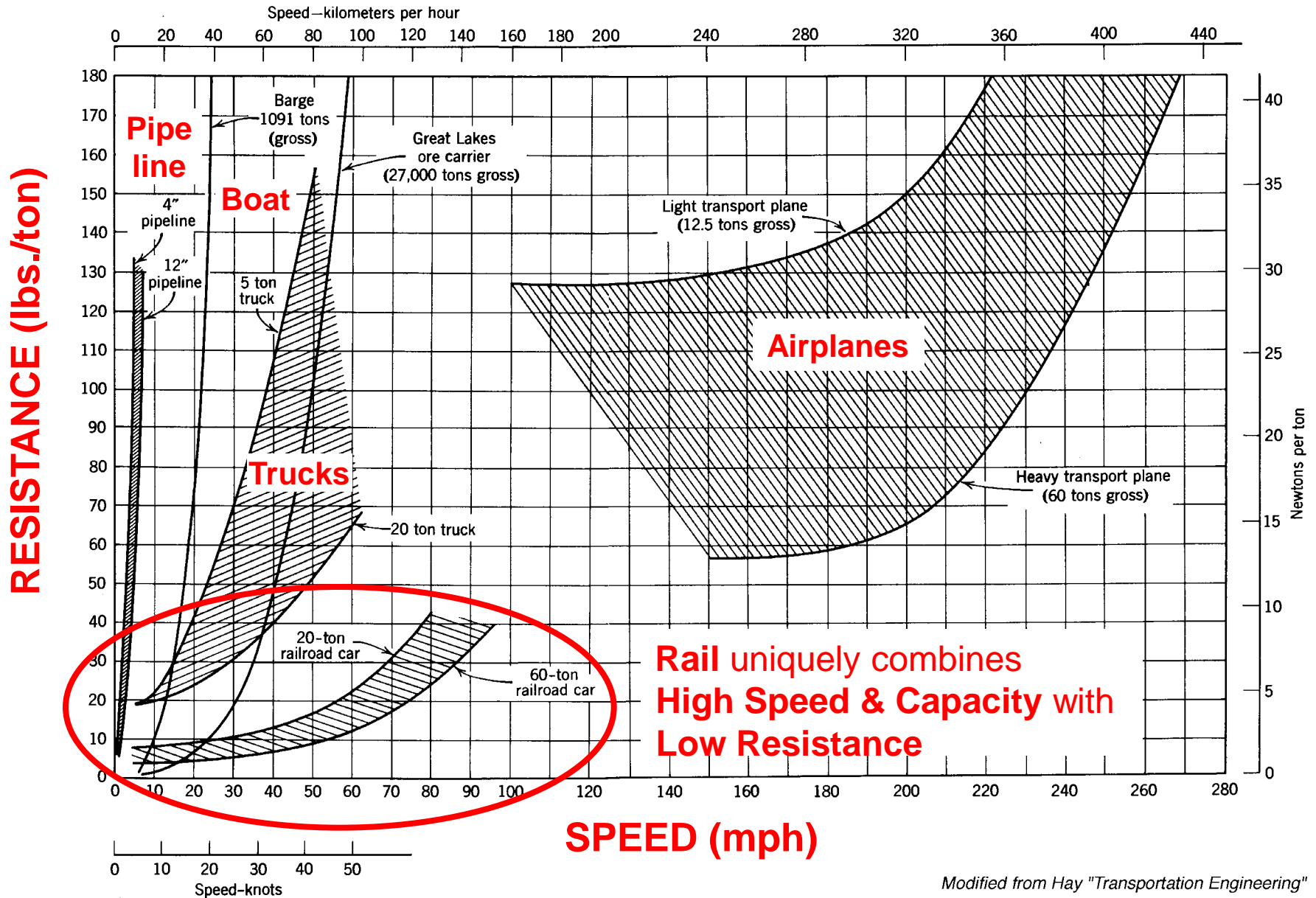


Transportation energy and work

- What are the two primary elements of transportation energy requirements?
 - **Resistance**
How much work is required to move something
 - **Energy efficiency**
How efficiently energy is converted into useful work



Speed and Resistance by Transport Mode



Railroad transportation efficiency

- Railroads produce transportation “output” more efficiently than their principal competition: trucks
- What is transportation “output”
 - Freight ton miles
 - Passenger miles
- So ***why*** are railroads so efficient?
 - ***Low rolling friction***
 - ***Large vehicles***
 - ***Trains***



Rolling friction

$$F_R = \mu_R W$$

where:

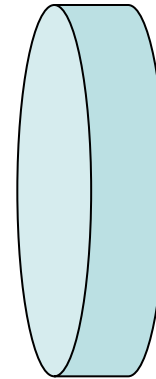
F_R = resistive force of rolling friction

μ_R = coefficient of rolling friction for the two surfaces

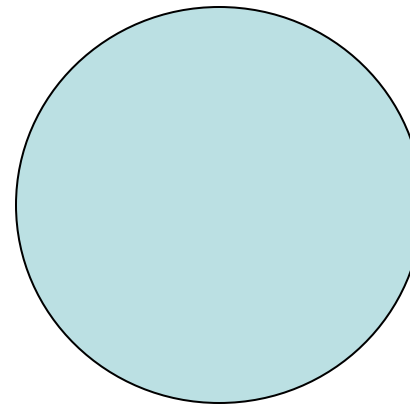
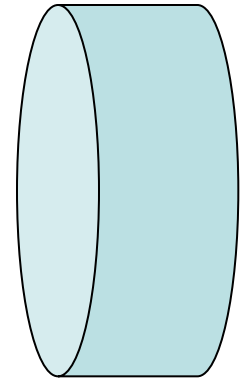
- proportional to the width of the wheel
- inversely proportional to its radius

W = weight

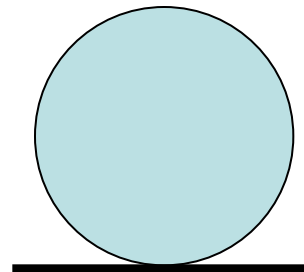
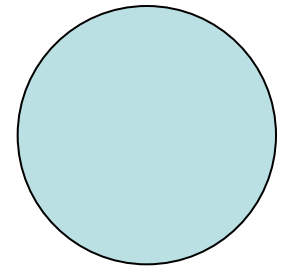
F_R is also inversely proportional to rolling surface hardness



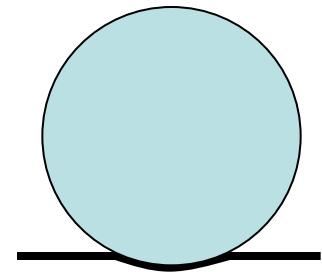
$$\mu_R < \mu_R$$



$$\mu_R < \mu_R$$



$$F_R < F_R$$



Steel Wheel on Steel Rail permits low coefficient of rolling friction (μ_R)

- **Steel wheel on steel rail** has lower rolling friction (μ_R) than rubber tire on pavement:
 - Steel wheel on rail: $\mu_R = 0.001$
 - Truck tire on pavement: $\mu_R = 0.006$ to 0.010
 - Tire is **6 to 10 times greater** than steel wheel
- Consequently lower rolling resistance
- Why?
- **Rubber tire on pavement**
 - Small effects of static friction and adhesion of the rubber
 - Major factor is the deformation of the tire while rolling under load
 - Pavement deflection also contributes
- Steel wheel and rail experience elastic deformation under load as well, ... *but much less*

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TIFF (Uncompressed) decompressor
are needed to see this picture.

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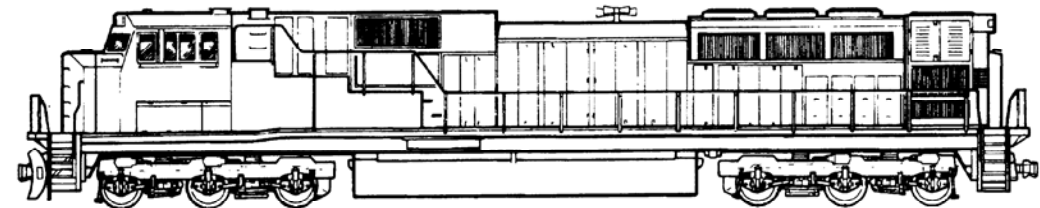
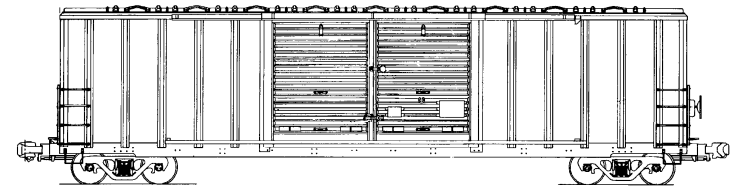
Operation of large, heavy vehicles is feasible because track structure is **STRONG** and efficiently designed

- Track system design and materials optimized to support **very** heavy loads
- Normal North American railroad axle load is 39 tons, compared to 8.5 for trucks



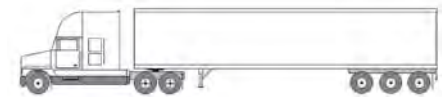
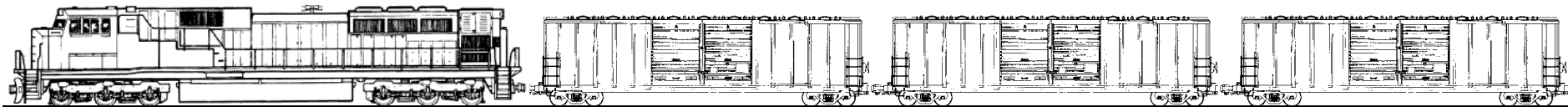
Large Size of rail vehicles permits economies of scale

- Strong railroad infrastructure allows larger, heavier vehicles than practical for highways
- Permits economies of scale
 - Larger vehicles can transport more weight with less resistance per unit
 - Larger engines convert energy to work more efficiently



Trains permit two more important economies of scale

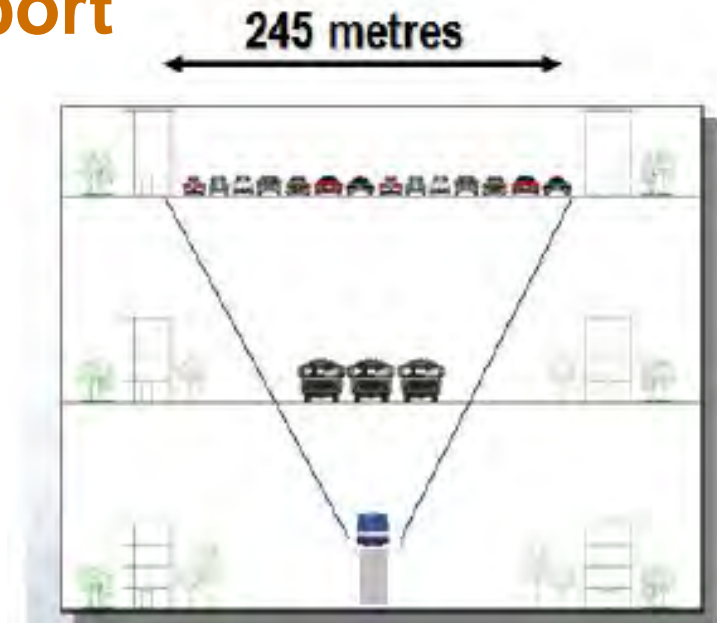
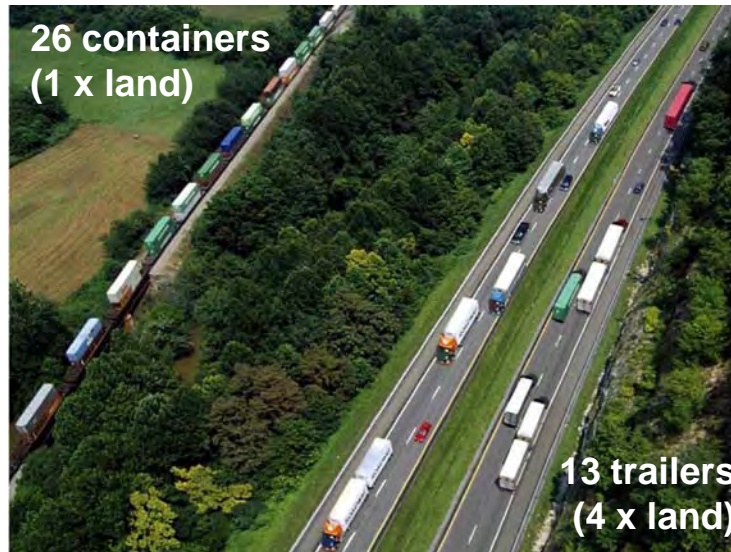
- The ability to operate many vehicles coupled together permits two more substantial economies of scale
 - **Labor:** one or two people can operate a single train with 100 to 150 cars (or more). Considering that each railcar is roughly equivalent to three trucks, the economies are substantial*.
 - **Energy:** close spacing of cars in train substantially reduces aerodynamic resistance compared to trucks. This effect is particularly important at higher speeds ($> 40\text{mph}$)



TRUCK trains are *possible*, but would we really want them?



Rail transport requires less land per unit of transport



Elevated train versus buses and private cars

- Transportation output per unit of land is much greater for rail compared to highway
- More units per vehicle (tons or people)
- Fewer vehicles, and they are consolidated into trains
- Easier to accommodate temporal differences in directional traffic



Measurement of train resistance

- Substantial research early in the 20th century led to the development of a general formula for train resistance
- Developed by W.J. Davis, often referred to as the “Davis Equation”

$$R_o = 1.3 + \frac{29}{w} + bV + \frac{CAV^2}{wn}$$

where:

R_o = resistance in lbs. per ton

w = weight per axle (= W/n)

W = weight of car

n = number of axles

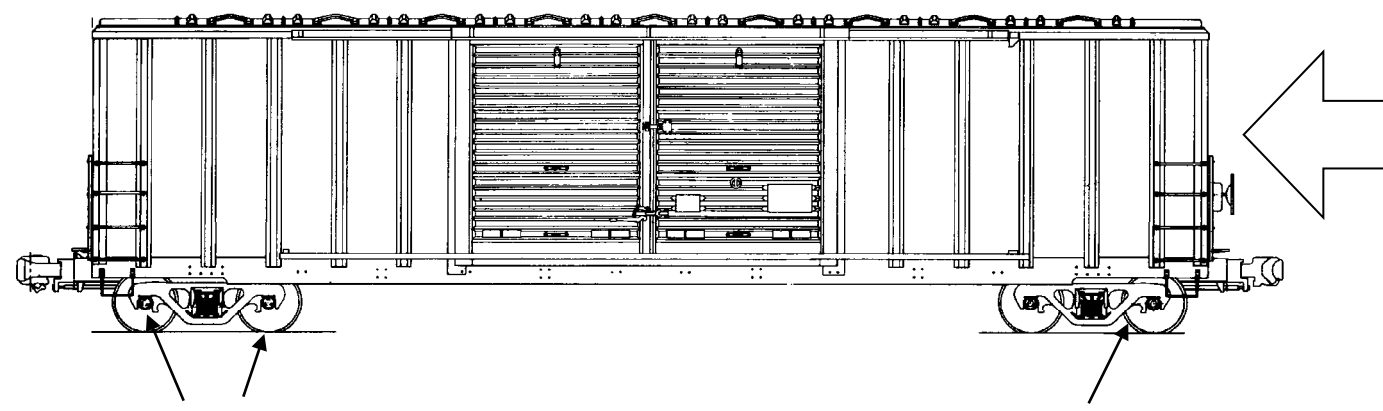
b = an experimental friction coefficient for flanges, shock, etc.

A = cross-sectional area of vehicle

C = drag coefficient based on the shape of the front of the train and other features affecting air turbulence etc.

- The Davis Equation has been substantially updated to reflect modern developments, but its basic form remains the same

Sources of rail vehicle resistance



A = resistances that vary with axle load (includes bearing friction, rolling friction and track resistance)

B = resistances that vary directly with speed (primarily flange friction and effects of sway and oscillation)

C = resistances that vary as the square of speed (affected by aerodynamics of the train)

A varies with weight ("journal" or "bearing" resistance)

B varies directly with velocity ("flange" resistance)

C varies with the square of velocity (air resistance)

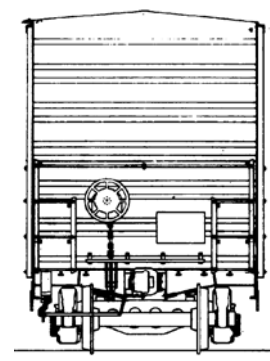
The general expression for train resistance is thus:

$$R = AW + BV + CV^2$$

where: R equals total resistance

W = weight

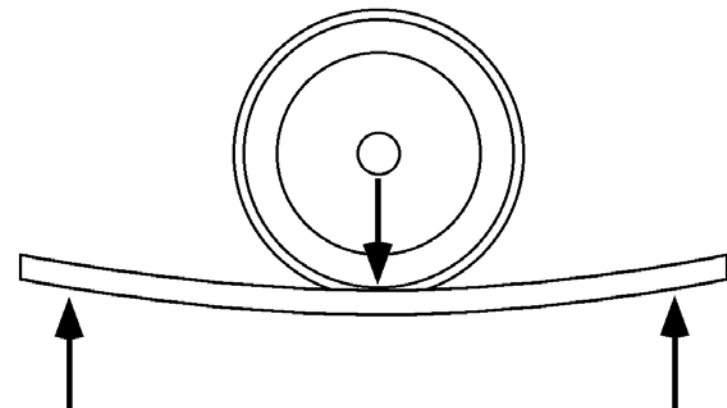
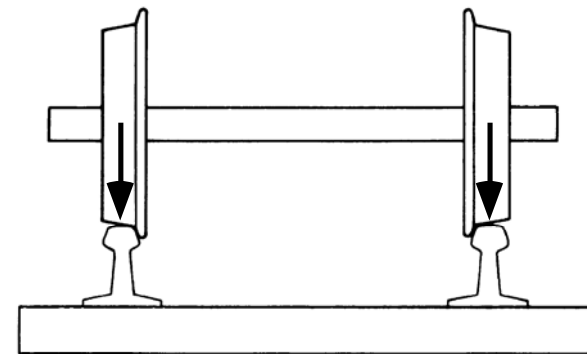
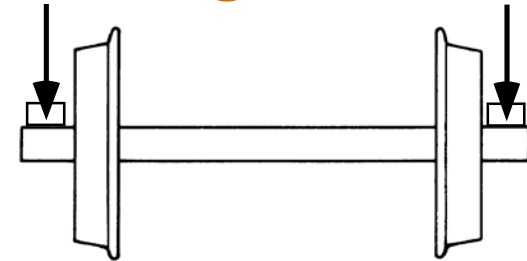
V = velocity



Cross-section of the vehicle, streamlining of the front & rear, and surface smoothness all affect air resistance

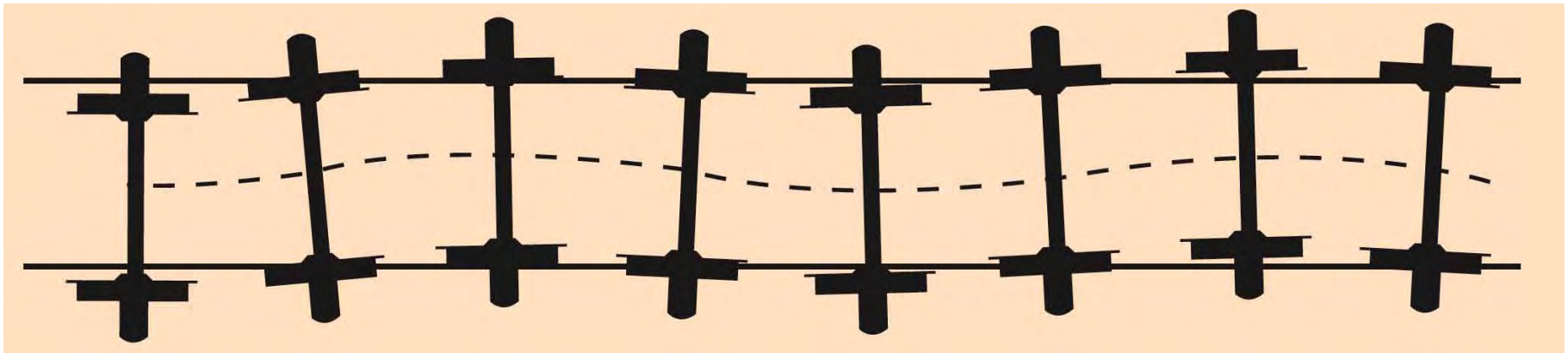
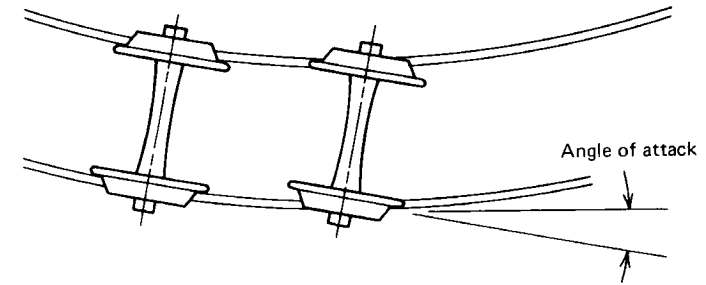
Resistances that vary with weight

- **Journal resistance**
 - Friction between journal and bearing
- **Rolling Friction**
 - Friction between wheel and rail due to “creepage” at interface
 - Minute elastic deformation of wheel and rail surfaces
- **Track Resistance**
 - Deformation of track structure
 - Consequent “uphill” running



Resistances that vary directly with speed

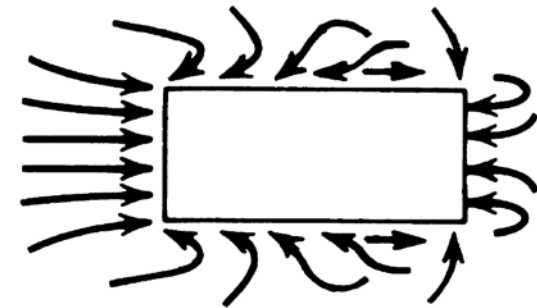
- **Flange contact**
 - consequent friction and impacts
 - rail lubrication reduces resistance on both curved and tangent track
- **Wheel/rail interface friction**
 - lateral movement between wheel tread and rail head
- **Oscillation** can also induce various other energy losses into:
 - vehicle suspension system (sway, bounce, buff, draft)
 - track structure



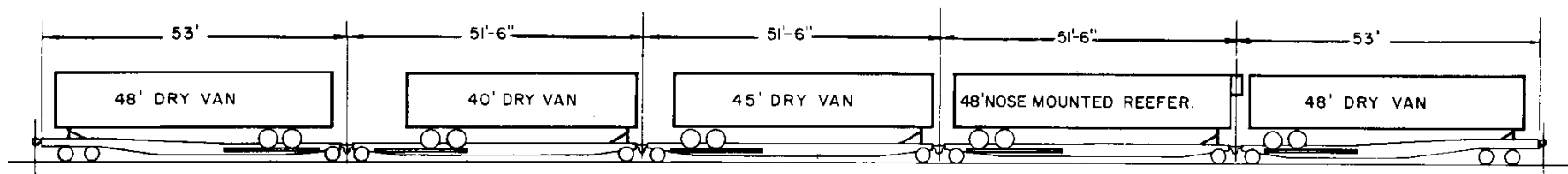
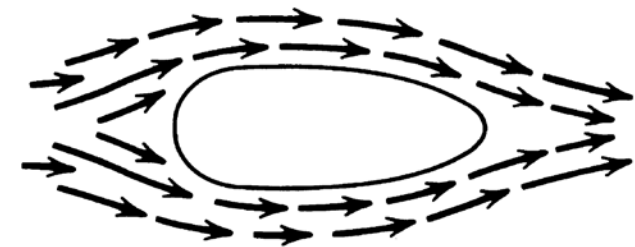
Resistances that vary as the square of speed

- Streamlining of vehicles and train has a substantial effect on air resistance as speeds increases
- Front and rear of train, as well as smoothness of sides affect air resistance
- Empty, open-top cars create turbulence that increases drag
- Wide spacing between cars also creates turbulence that increases drag
- The aerodynamics of the whole train may be more important than that of individual vehicles

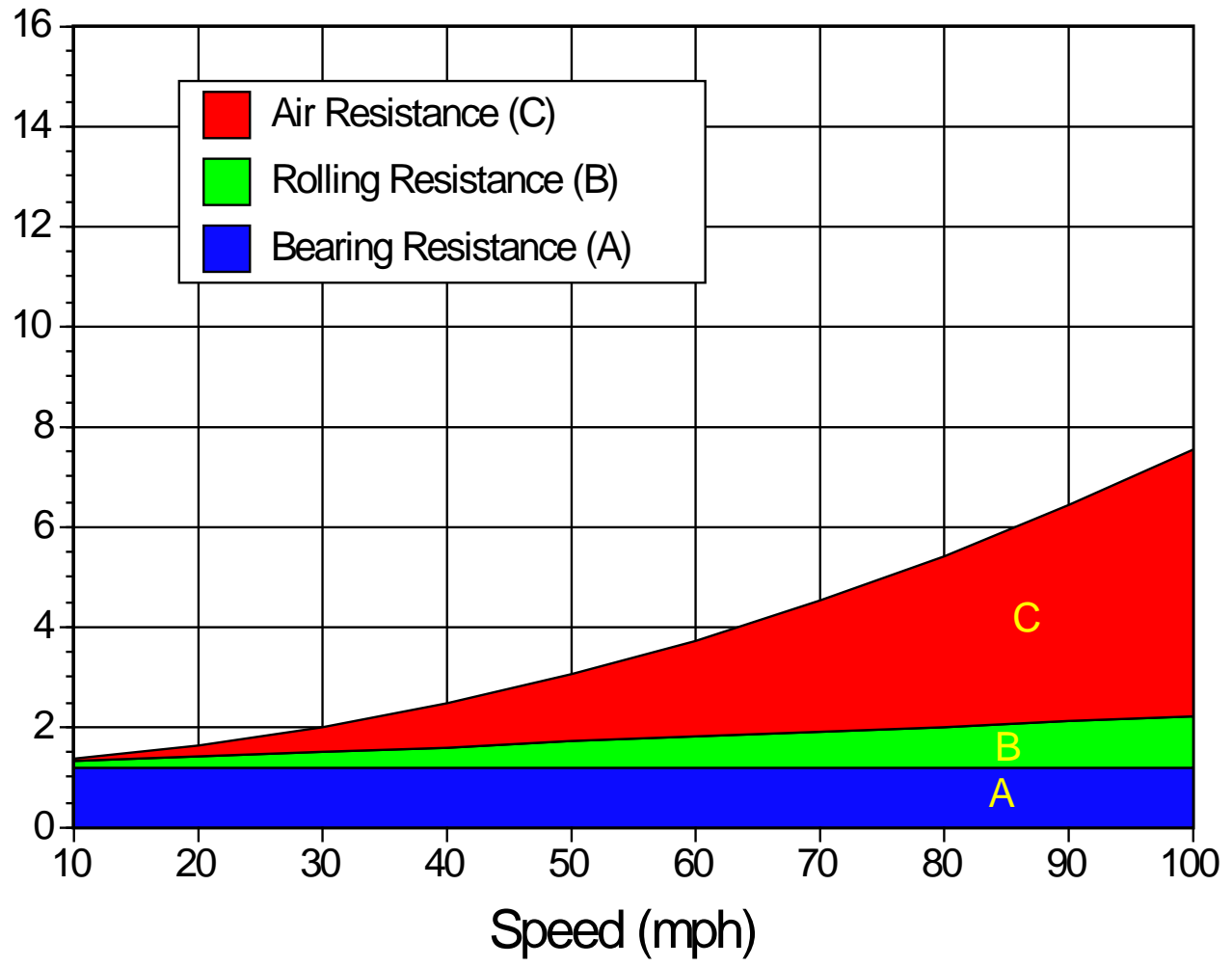
Non-aerodynamic



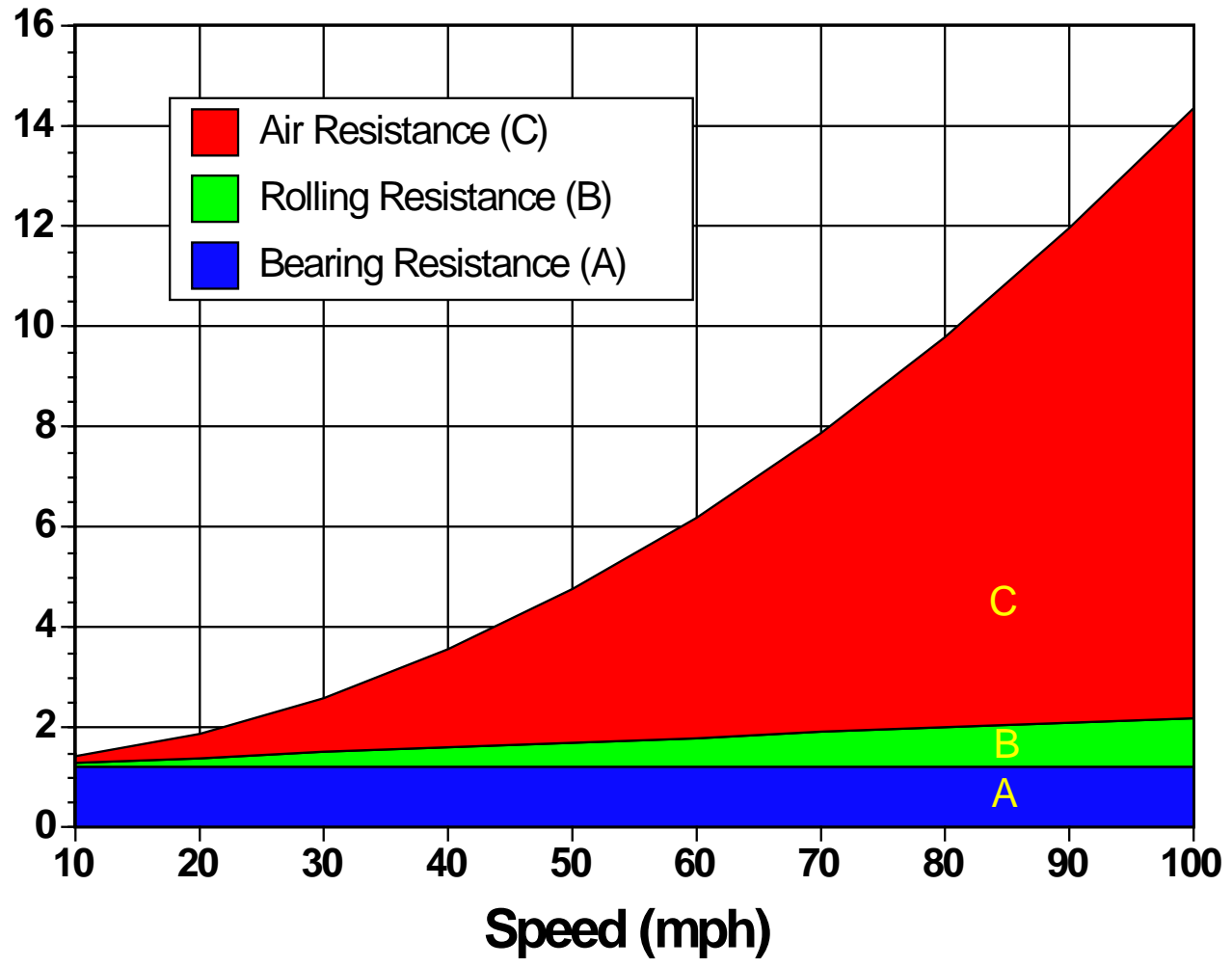
Aerodynamic



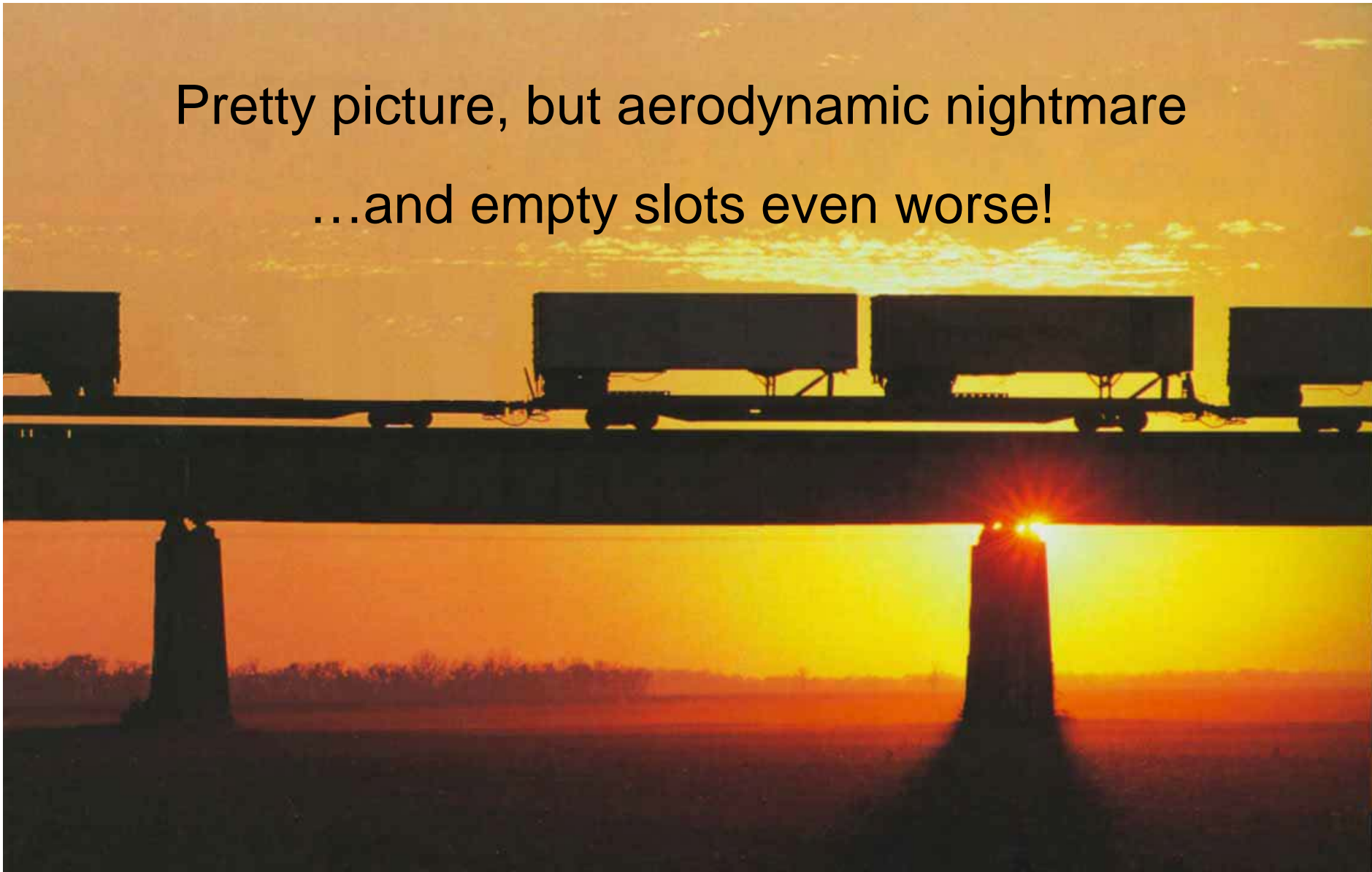
Conventional Freight Train Resistance



Intermodal (TOFC) Freight Train Resistance

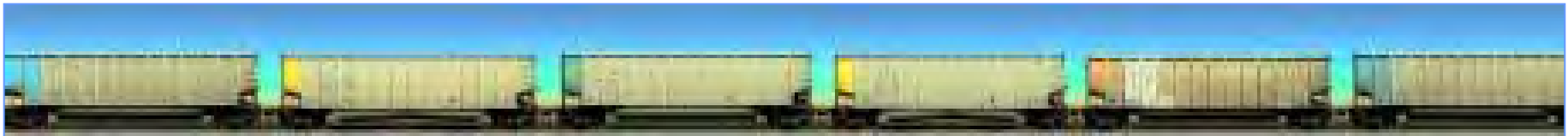


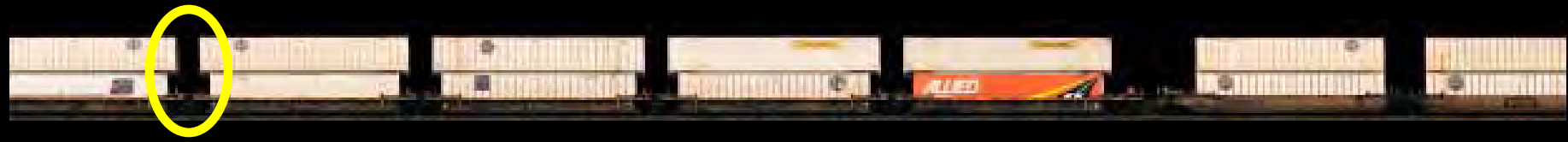
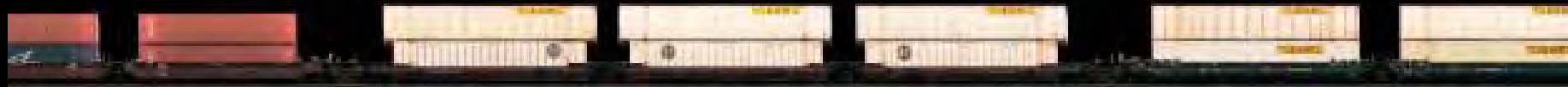
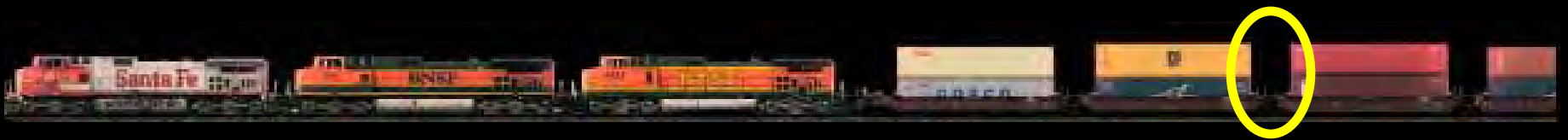
Pretty picture, but aerodynamic nightmare
...and empty slots even worse!



Improving intermodal train energy efficiency

- Intermodal (IM) freight is the largest source of revenue for US freight railroads and the fastest growing segment of their business
- IM freight is the least energy efficient in comparison to other types of rail freight
 - High speed necessary to compete with trucks
 - Poor aerodynamics due to large air gaps between and beneath loads
- Continued growth of this business indicates need to improve its energy efficiency





“Gap Length” and “Position in Train” are the two most important factors to IM train aerodynamics



Based on the wind tunnel testing of rail equipment, three important factors to IM train aerodynamics were identified:

1. Gap Length between the IM loads
2. Position in Train
3. Yaw Angle: wind direction (canceled out over the whole route)



BNSF Transcontinental Mainline



Long Beach/ Los Angeles

Chicago

LA to Chicago over 2,000 miles

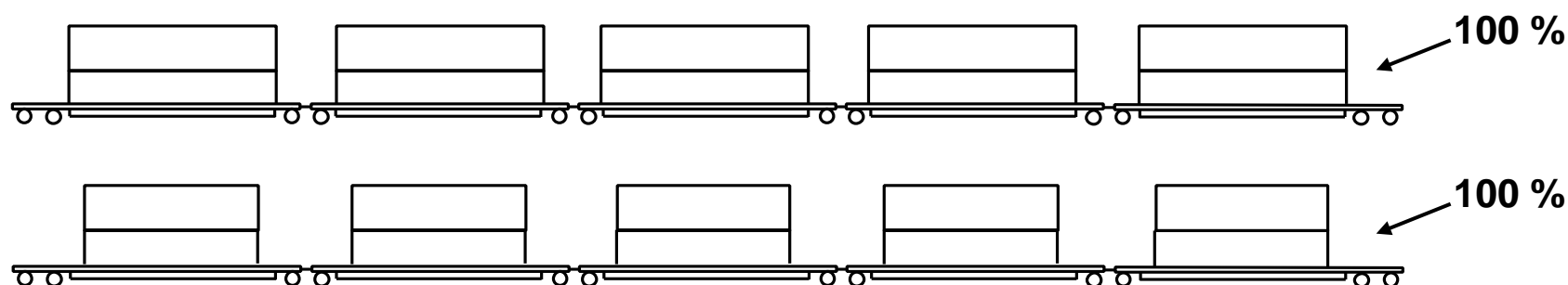


Slot utilization measures the percentage of slots on IM cars are used for loads

Maximizing slot utilization improves train energy efficiency because it eliminates empty slots and the consequent large gaps

However, it does not account for the *size of the space compared to the size of the load*

Two trains may have identical slot utilization, but different loading patterns and aerodynamic resistance

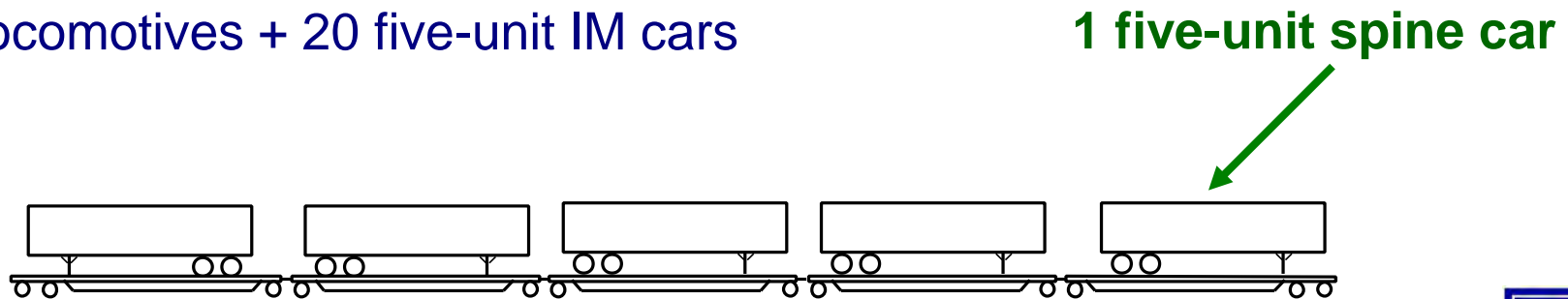


Not the “Right Car” for the “Right Loads”

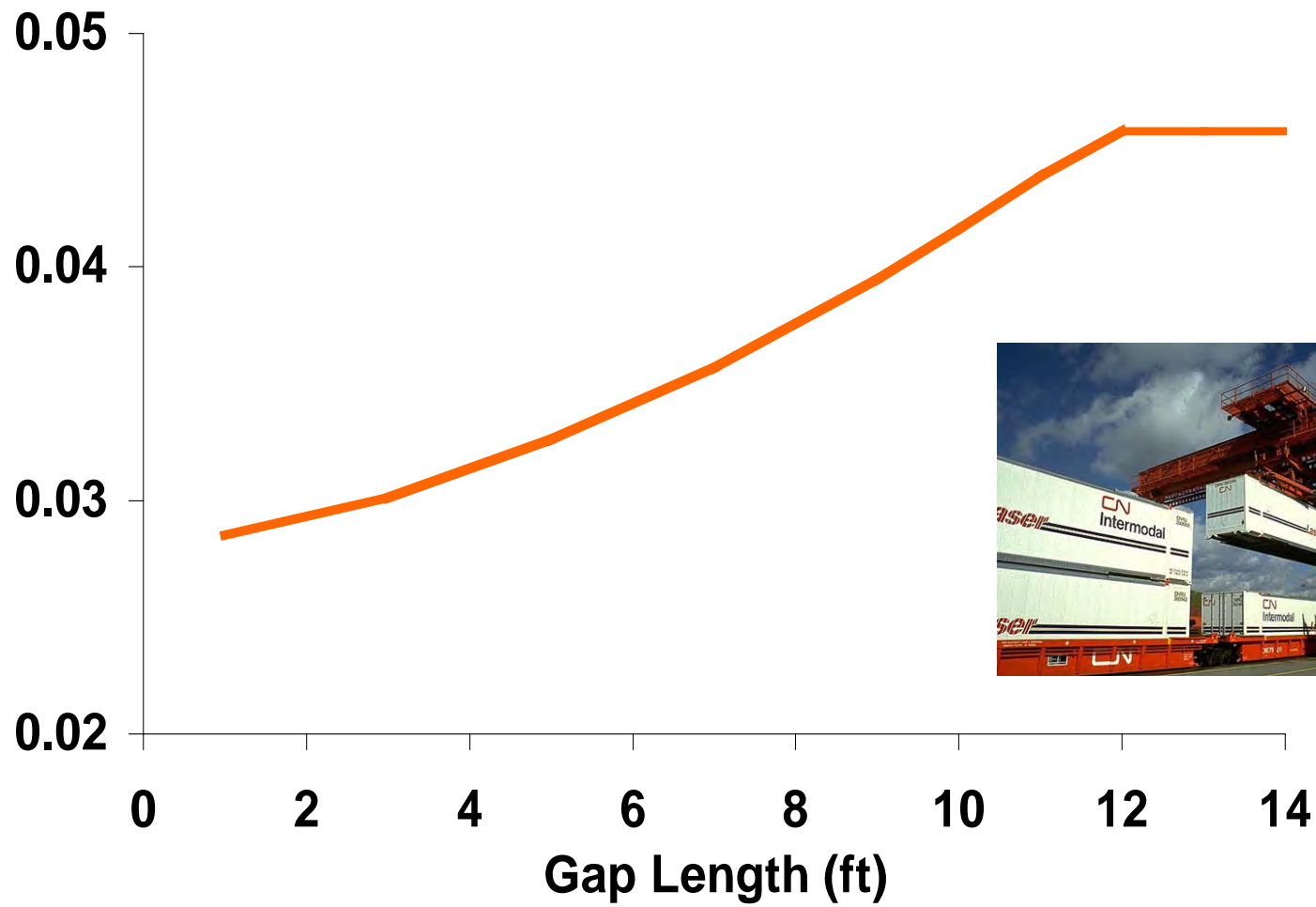


Train Energy Model and Aerodynamic Subroutine were used to conduct efficiency analysis

- General Train Resistance Equation: $R = A + BV + CV^2$
 - Bearing and rolling resistance are primarily affected by weight
 - Aerodynamic coefficient is determined according to loading pattern
- Fuel Consumption: AAR Train Energy Model (TEM)
- Representative Train:
 - 3 locomotives + 20 five-unit IM cars



Larger gaps resulting in a higher aerodynamic coefficient and greater resistance



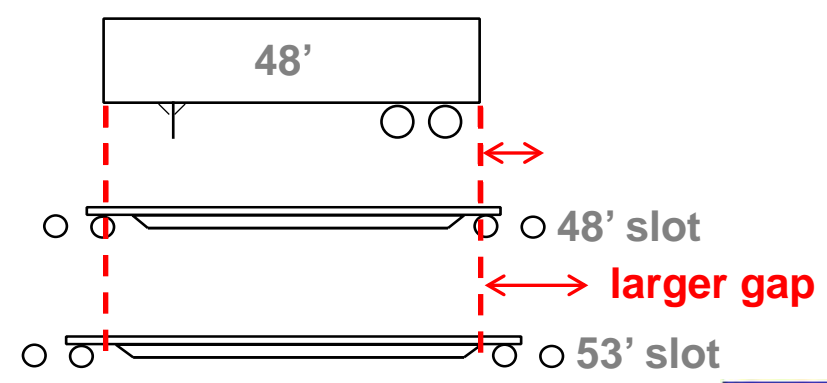
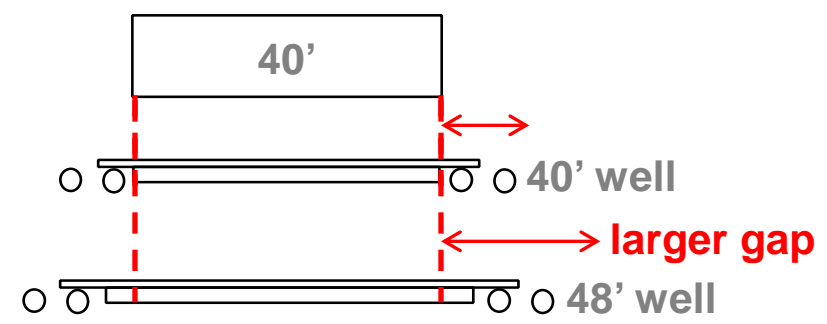
Equipment matching matches IM loads with railcars so as to minimize gaps and maximize efficiency

Capacity of well and spine cars is usually constrained by the length of the loads

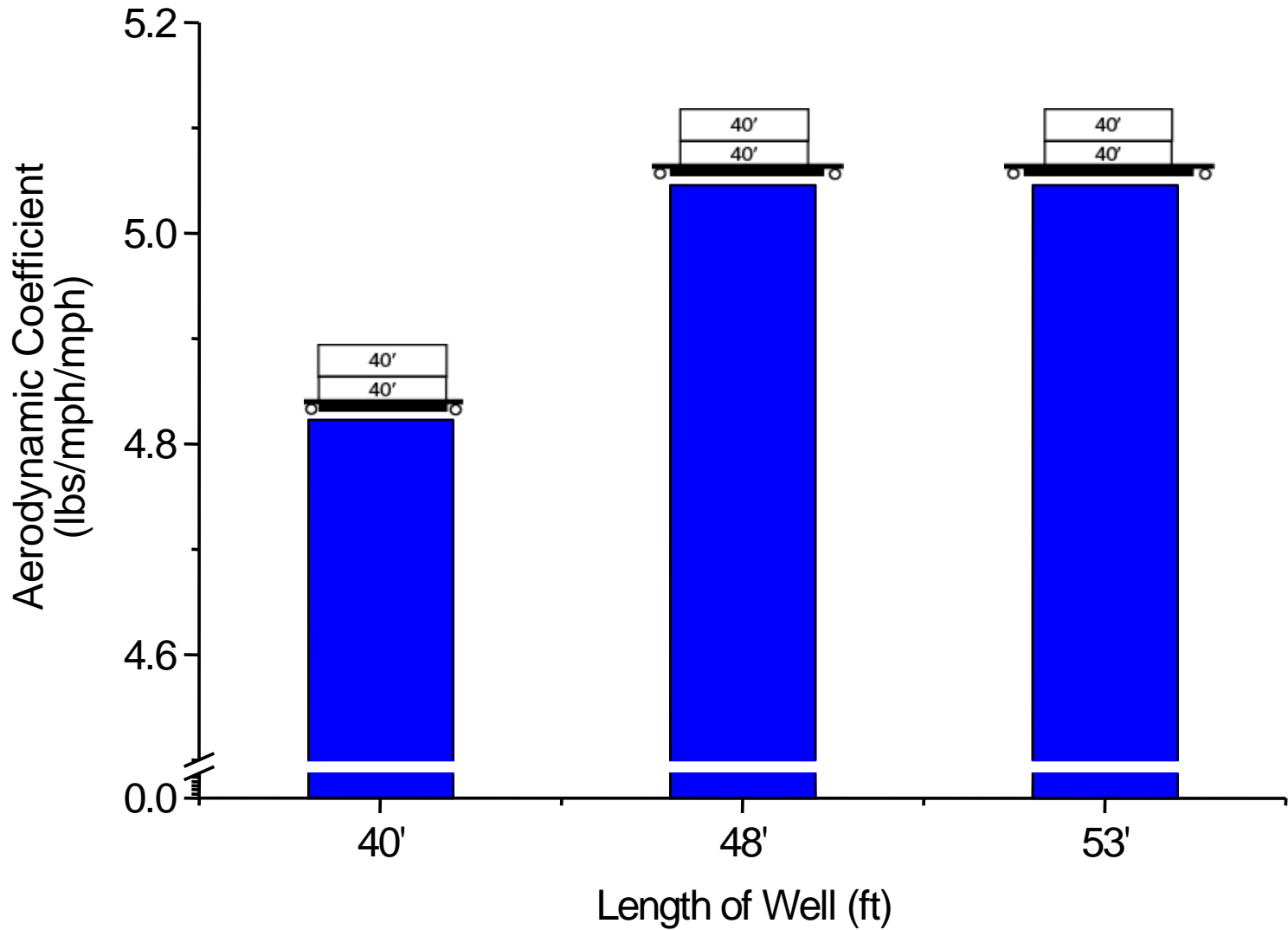
Equipment matching matches IM loads so as to minimize gaps

Example:

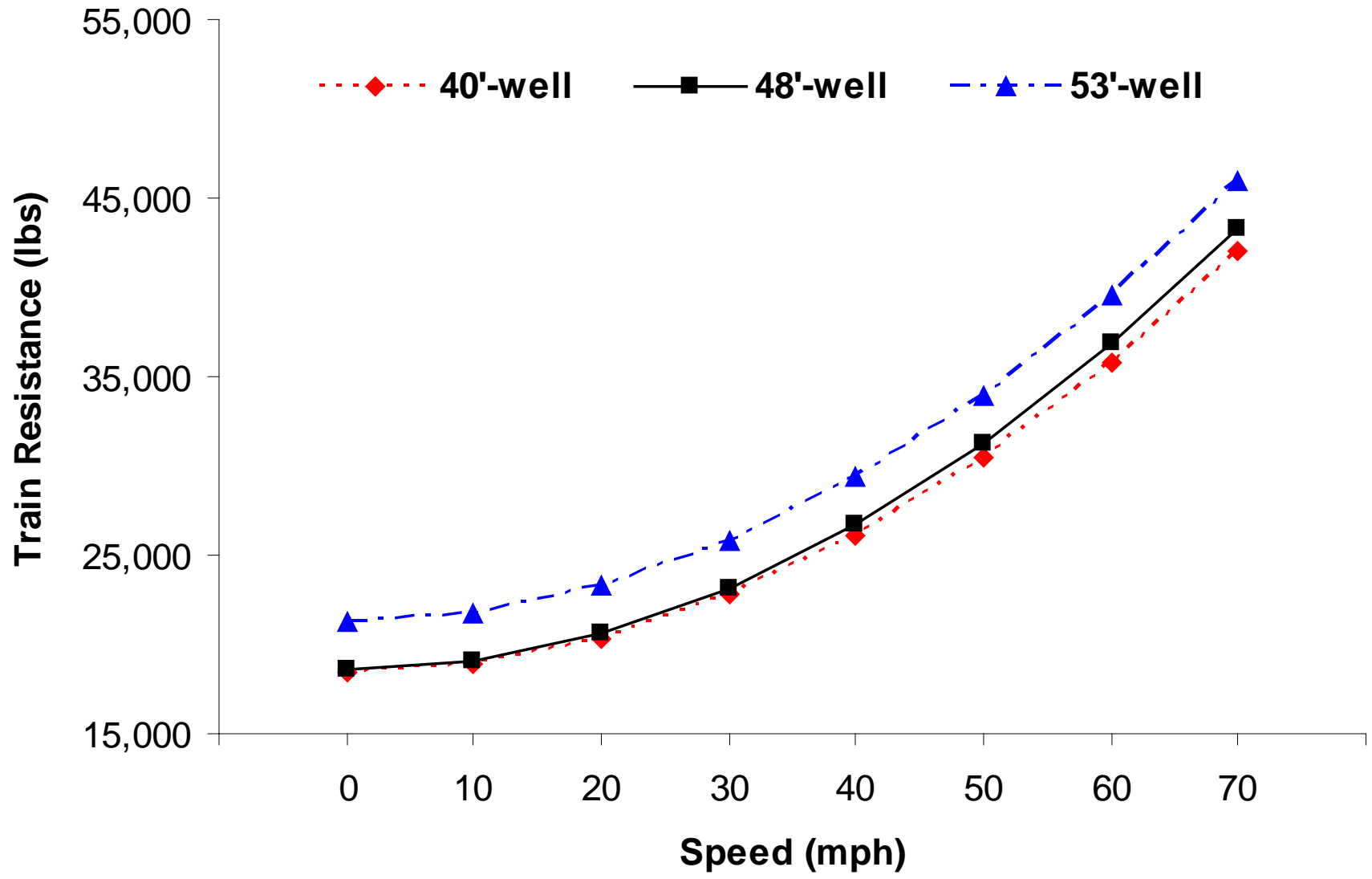
- 40' container in 40' well car, rather than a 48' well car
- 48' trailer in 48' slot spine car, rather than car with 53' slot



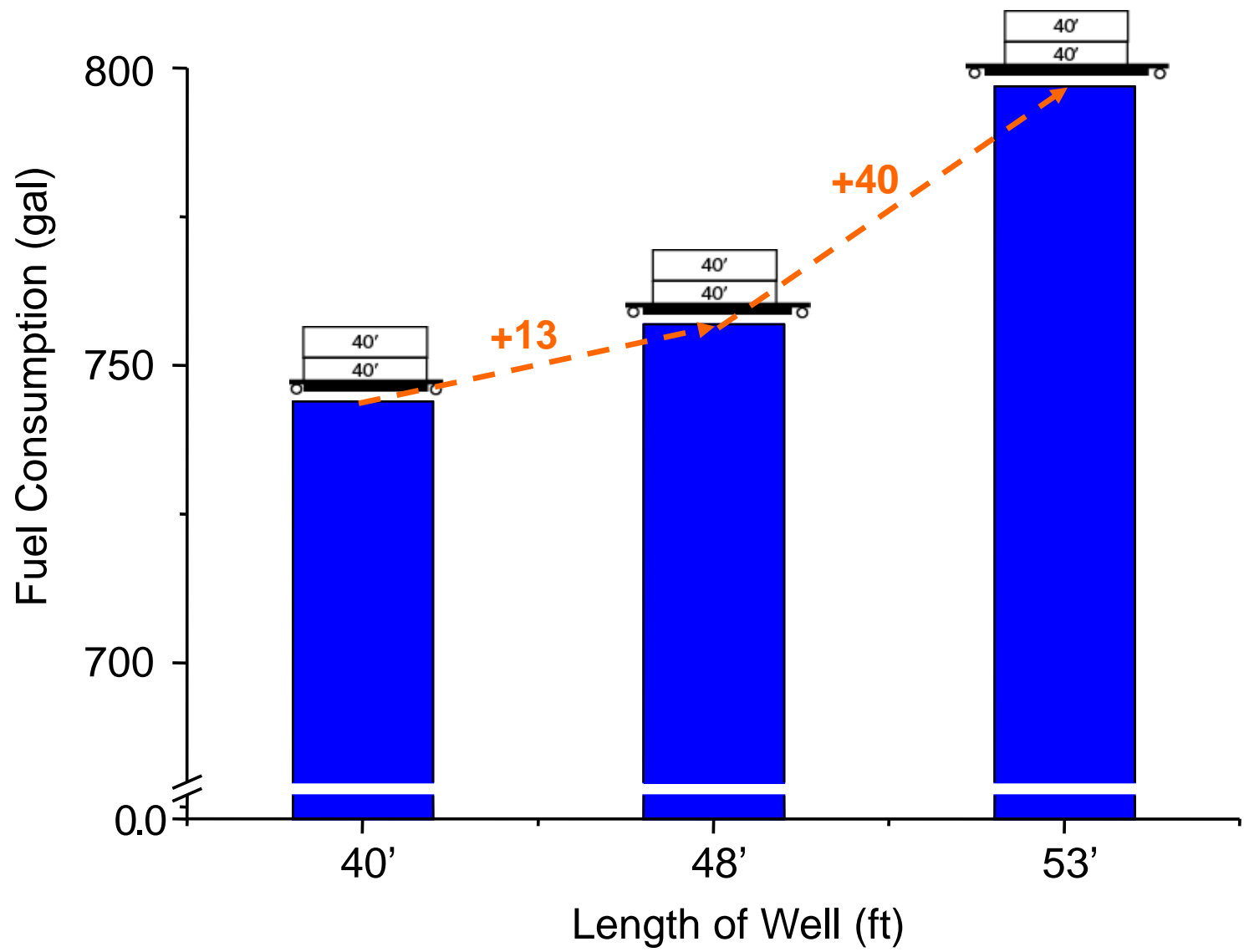
Aerodynamic Coefficient of 40' IM Loads in Various Sized-well Cars



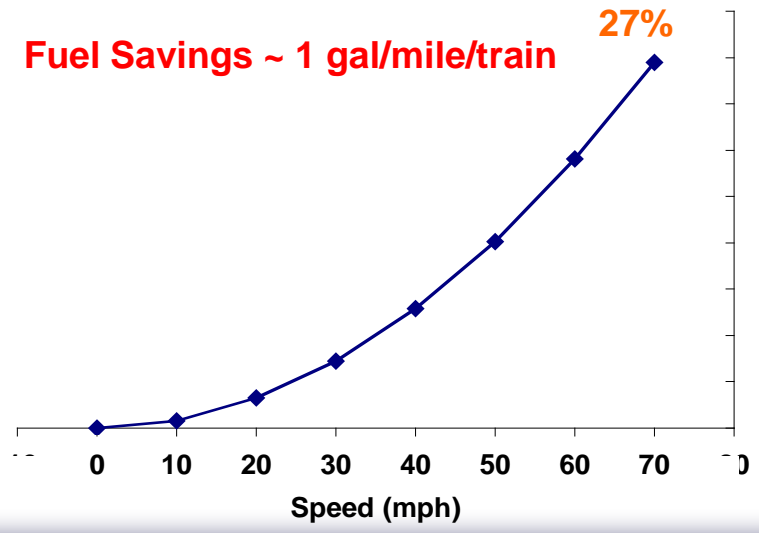
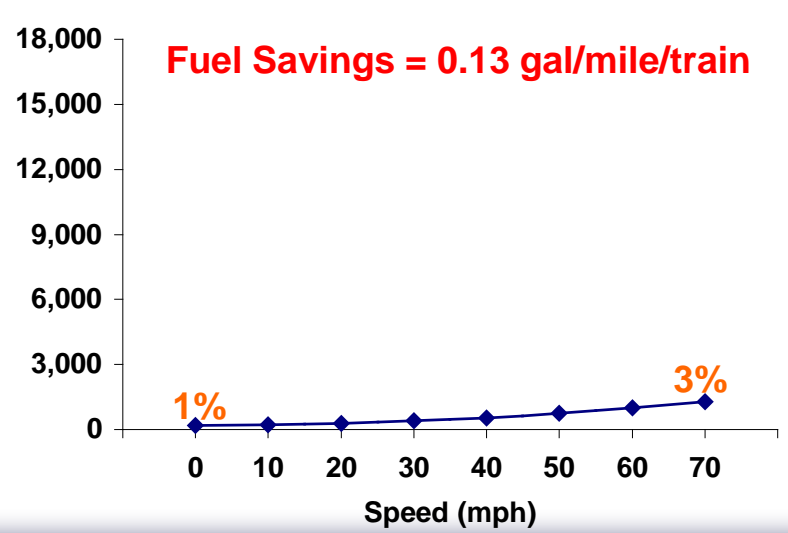
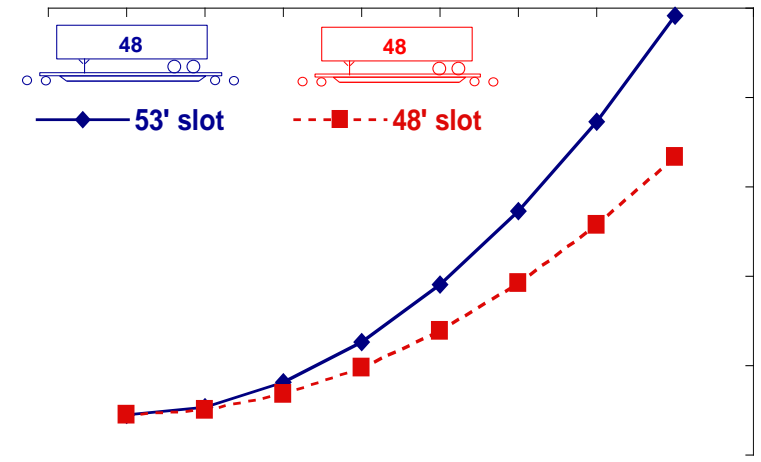
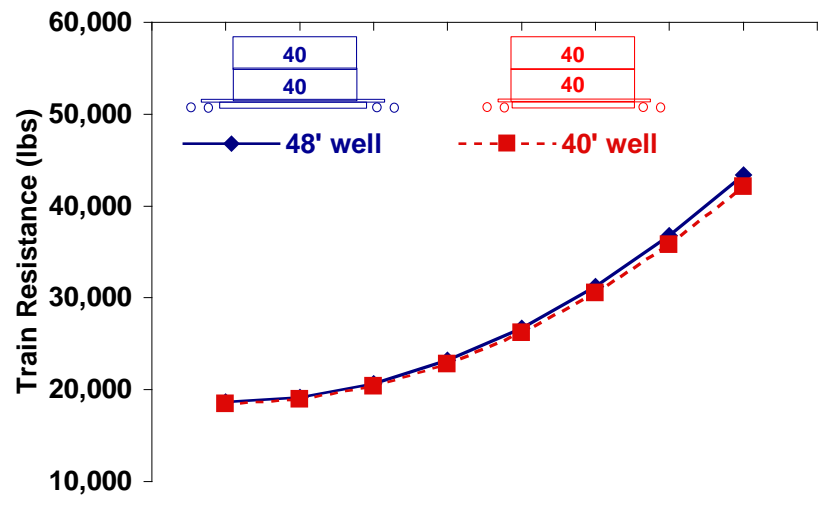
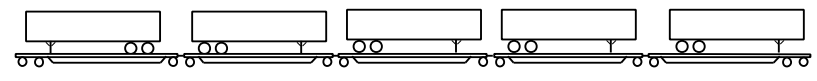
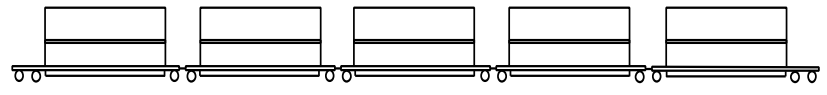
Total Train Resistance = Weight + Aerodynamics



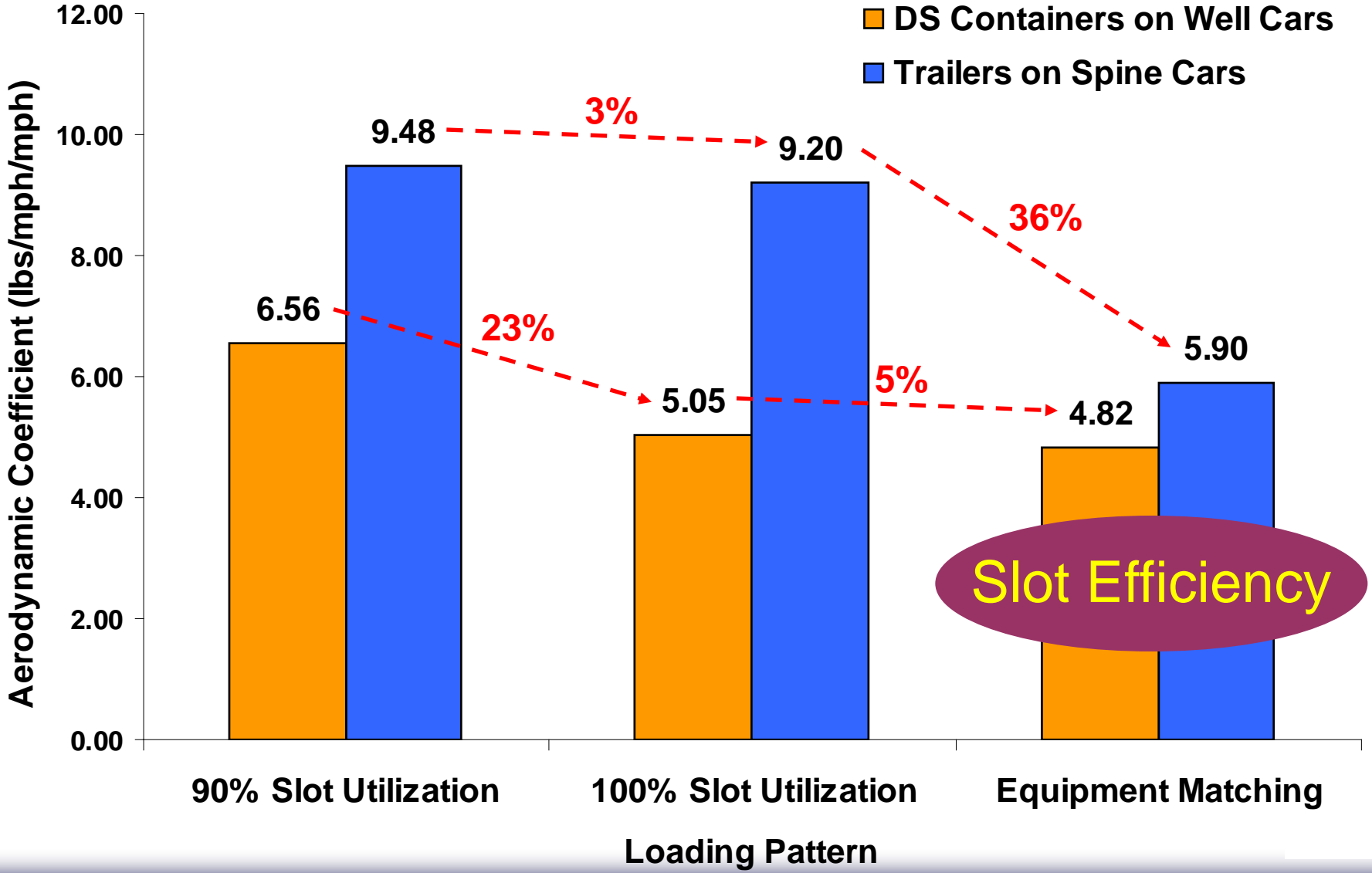
Fuel Consumption over an 103-mile Route



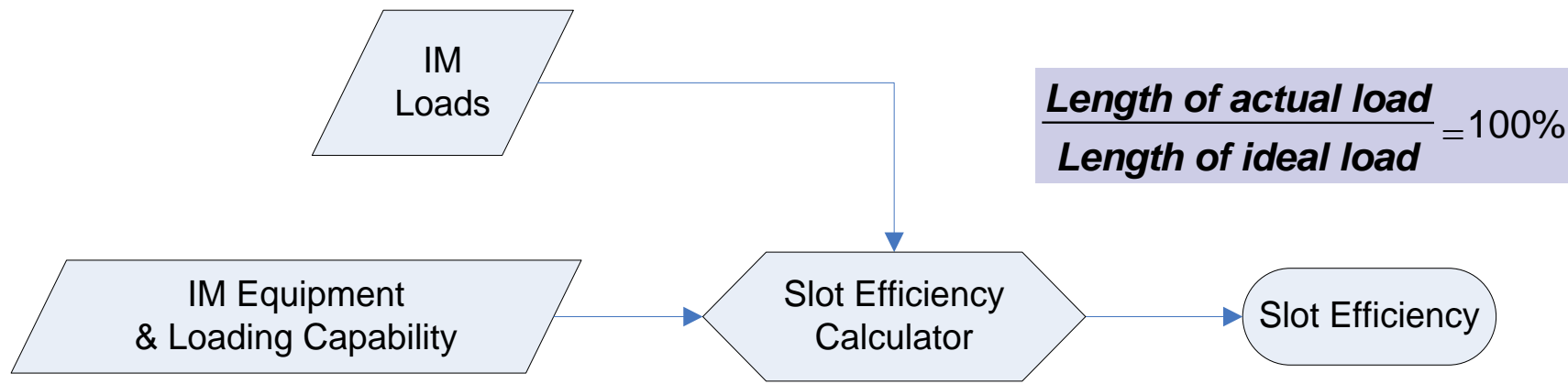
Matching can save as much as 1 gal/mile



Loads should be assigned not only based on slot utilization but also "slot efficiency"



Using “Slot Efficiency” to monitor the loading efficiency of IM trains



Slot efficiency represents the loading efficiency by comparing the difference between the actual and ideal loading configuration

Every slot in each type of railcar has an ideal load that can be determined by using the loading capability of each railcar acquired from UMLER

Slot efficiency is similar to slot utilization except that it also factors in the energy efficiency of the load-slot combination

Right Cars for the Right Loads



Aerodynamic Loading Assignment Model (ALAM) optimizes the aerodynamic efficiency of IM trains

Minimize *Total Adjusted Gap Length*

subject to:

Railcar Loading Capability

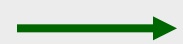
(including railcar accommodation ability, train schedule & blocking plan)

Double Stack Constraints

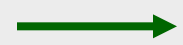
Weight Constraints for Every Unit

Length Constraints for Every Slot

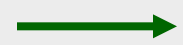
Railcar Inventory
(car initial & #)



Blocking Plan



Train Schedule



Load Inventory
(weight & Length)

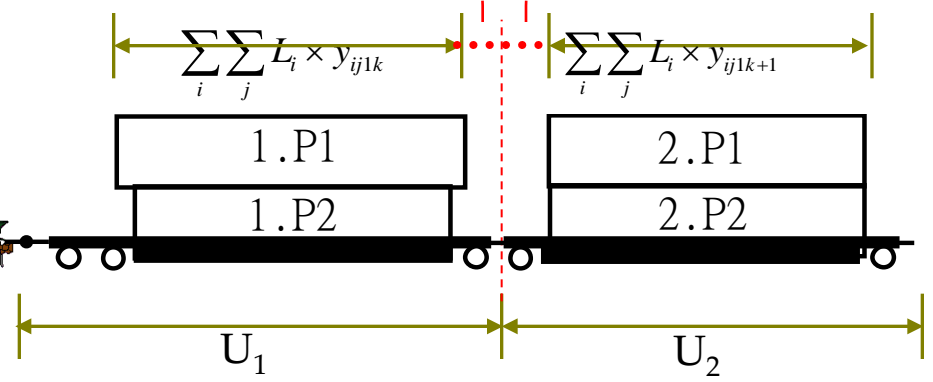


Optimal Loading Pattern

Updated Load Inventory

Z is the total “adjusted” gap length within the train

$$z = \frac{A_1}{2} \left(U_1 - \sum_i \sum_j y_{ij1} L_i \right) + \frac{\sum_{k=1}^N A_{k+1}}{2} \left[\left(U_k - \sum_i \sum_j y_{ij1k} L_i \right) + \left(U_{k+1} - \sum_i \sum_j y_{ij1k+1} L_i \right) \right]$$



Where:

- i = Type of the load (40', 48', 53' etc.)
- j = Load number within the specific type
- k = Unit number (1,2,...,N)
- p = Position in the unit (P1 or P2)
- A_k = Adjusted factor of k^{th} gap
- U_k = Length of k^{th} unit
- L_i = Length of i^{th} type load (ft)
- y_{ijkl} = 1 if j^{th} load in i type was assigned to k^{th} unit L^{th} position; 0 otherwise



Aerodynamic Loading Assignment Model (ALAM)

Min Z ← minimize total adjusted gap length

$$\text{s.t. } \sum_p \sum_k y_{ijpk} R_{ipk} \leq 1 \quad \forall i, j$$

$$y_{ijpk} \leq R_{ipk} \quad \forall i, j, p, k$$

} loading capabilities

$$40 - \sum_{i \in C_L} \sum_j y_{ij2k} L_i \leq \Phi(1 - x_k) \quad \forall k \text{ (such that } \delta_k = 1)$$

$$\sum_{i \in C_L} \sum_j y_{ij1k} \leq x_k \quad \forall k \text{ (such that } \delta_k = 1)$$

$$\sum_{i \in T_L} \sum_j y_{ij2k} \leq 2 \times (1 - \sum_{i \in C_L} \sum_j y_{ij1k}) \quad \forall k \text{ (such that } \delta_k = 1)$$

} double-stack rules

$$\sum_i \sum_j \sum_p y_{ijpk} w_{ij} \leq W_k \quad \forall k$$

← weight constraint

$$\sum_i \sum_j y_{ijpk} L_i \leq Q_{kp} \quad \forall k, p$$

← length constraint

$$y_{ijpk}, x_k = 0, 1$$

Where: R_{ipk} = Loading capability

w_{ij} = Weight of j^{th} load in i type

W_k = Weight limit of k^{th} unit

Q_{kp} = Length limit of position p in k^{th} unit

δ_k = 1 for well-car unit; 0 otherwise Φ = A large positive number

x_k = 1 if the top slot of k^{th} Unit can be used; 0 otherwise



The front of the train experiences the greatest aerodynamic resistance

Unit (k) #	Drag area ($C_D A$) (ft ²)
1 (locomotive)	31.618
2	28.801
3	26.700
4	25.133
5	23.963
6	23.091
7	22.440
8	21.954
9	21.591
10	21.320
100	20.466

base value

Placing loads with shorter gaps in the frontal position generates less aerodynamic resistance

Objective:

Minimize the total “adjusted” gap length within the train

(adjusted gap length = adjusted factor x actual gap length)



Applying ALAM to the example train can save 0.95 gallons per mile for one train

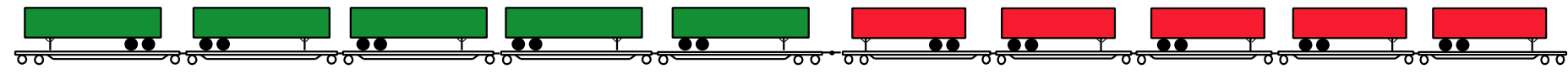
Loads: fifty , fifty , fifty  ← 150 loads

Train: ten 5-unit 53-foot-slot spine cars followed by ten 5-unit 48-foot-slot spine cars } 100 slots

Optimum based on ALAM = 514 (ft)



Worst case by manual assignment = 1170 (ft)

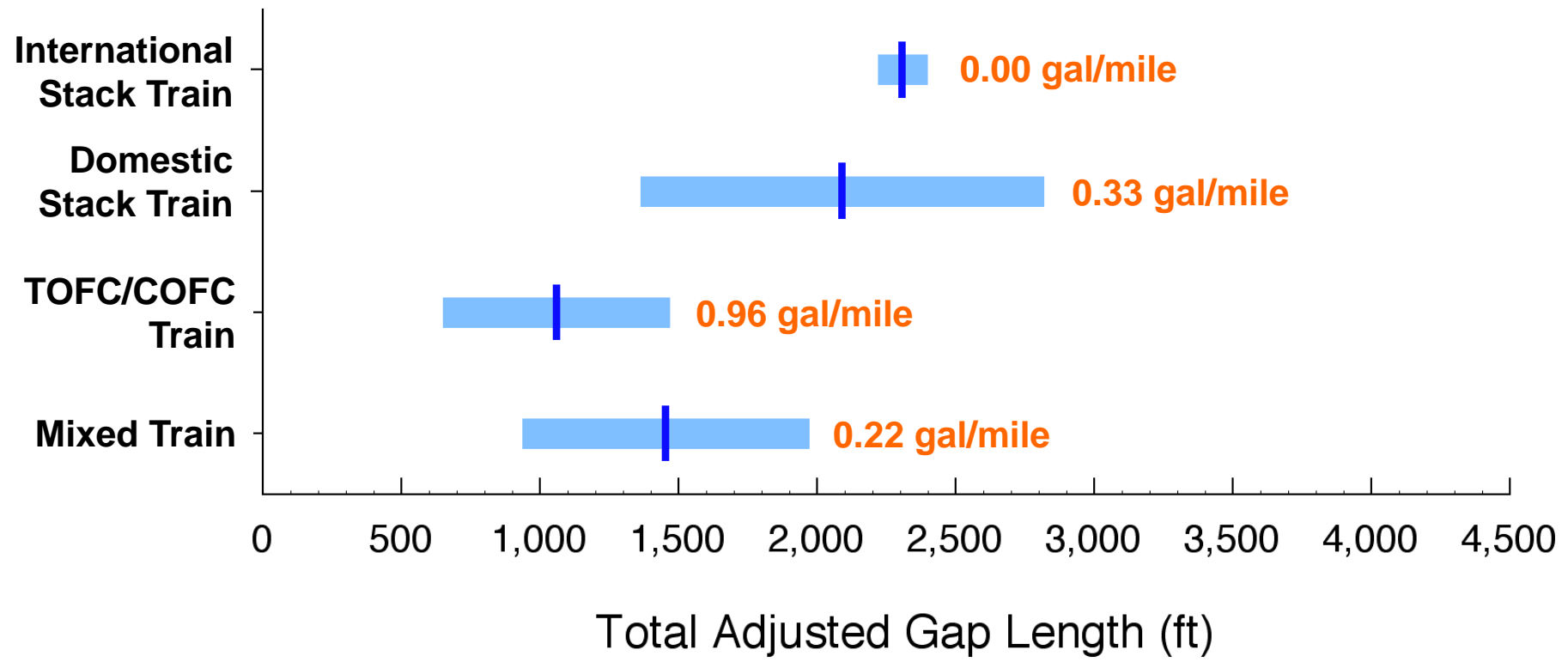


Fuel savings is 0.95 gallons/mile/train

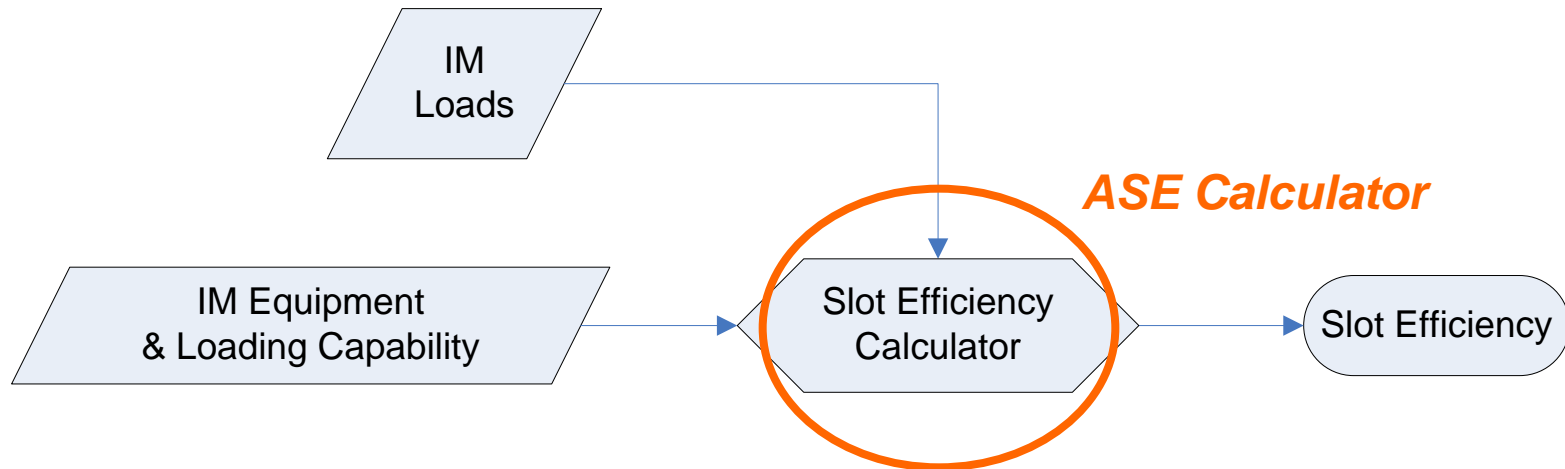


Applying ALAM to four general types of IM trains

Type	C20	C40	C45	C48	C53	T20	T28	T40	T45	T48	T53	Total Loads
Intl. Stack Train	32	184	8	0	0	0	0	0	0	0	0	224
Domestic Stack Train	28	88	9	17	102	0	0	0	0	0	0	244
TOFC/COFC Train	0	0	0	0	0	11	31	0	30	35	24	131
Mixed Train	32	22	0	6	59	0	2	2	2	15	33	173



Using “Adjusted Slot Efficiency (ASE)” to monitor the loading efficiency of IM trains



$$ASE = \text{Adjusted Factor} = \frac{\text{Length of actual load}}{\text{Length of ideal load}} = 100\%$$

**ASE accounts for both “Gap Length” and “Position in Train” effects*



Conclusions & Recommendations

A train can be more efficiently operated if loads are assigned based on **adjusted slot efficiency**

Filling empty slots with empty containers or trailers also reduces aerodynamic resistance thereby improving energy efficiency

Uncoupling empty railcars from the end of loaded intermodal trains when practical to reduce weight and fuel consumption

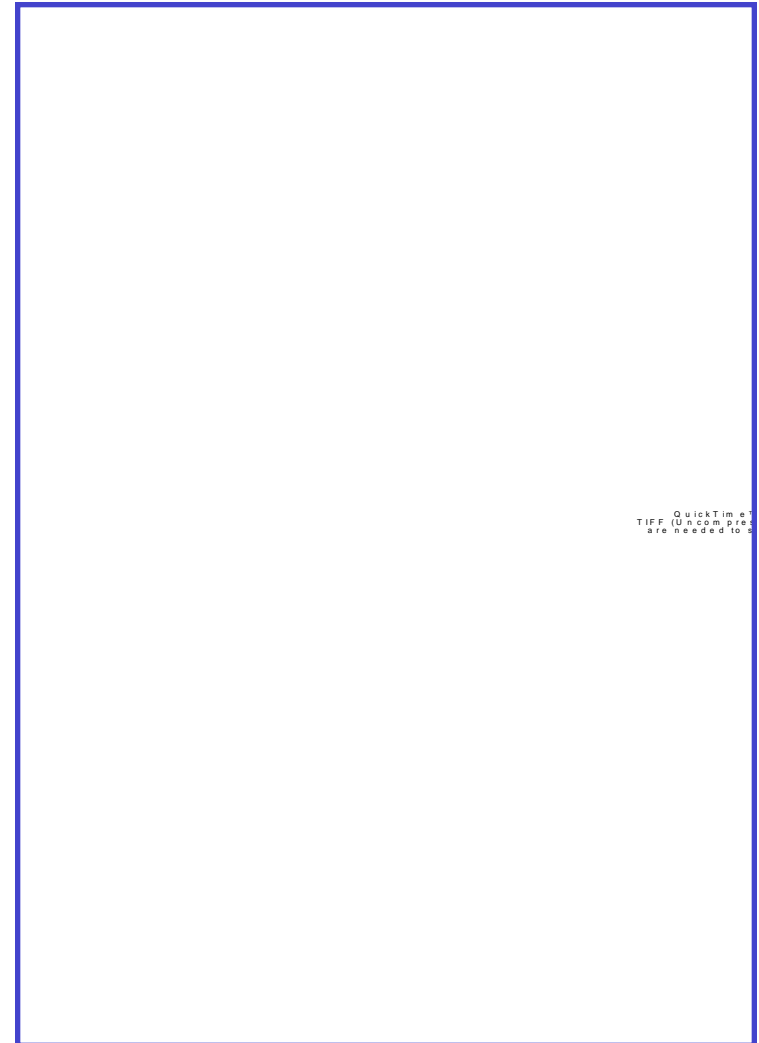
By using the **aerodynamic loading assignment model (ALAM)**, the potential fuel savings can be as much as 0.96 gal/mile/train

A photograph showing the silhouettes of several intermodal train cars (flatcars with containers) against a bright, orange and yellow sunset sky. The train is on a track, and the ground is dark. The word "Questions?" is overlaid in white text on the left side of the image.

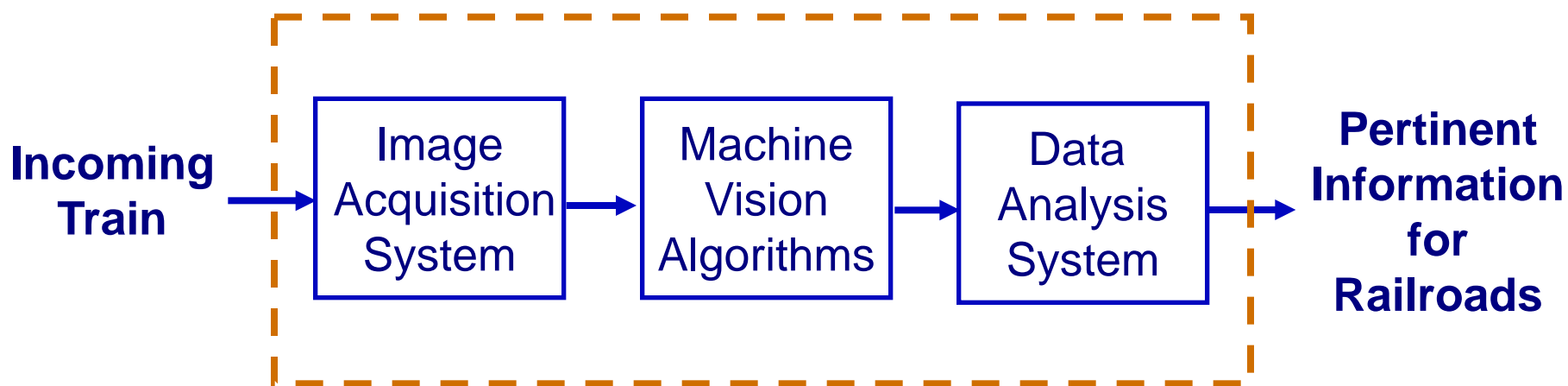
Questions?

Automated monitoring of IM loading using machine vision

- Due to the high volume, speed and length of their intermodal traffic, BNSF was interested in developing technology to automatically monitor how well they were loading their trains
- Sponsored research at UIUC to develop this capability.
- Railroad Engineering Program teamed with Computer Vision and Robotics Lab in Beckman Institute to develop an automated, machine vision system for this purpose



Primary Machine Vision System Components

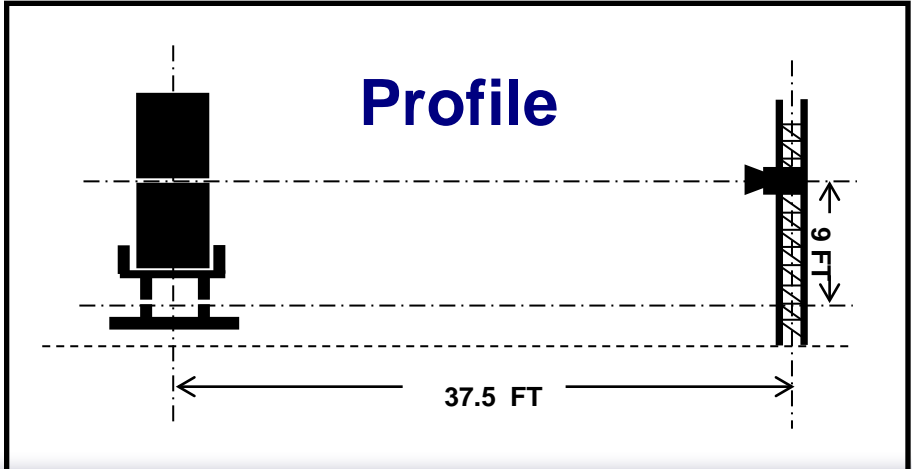
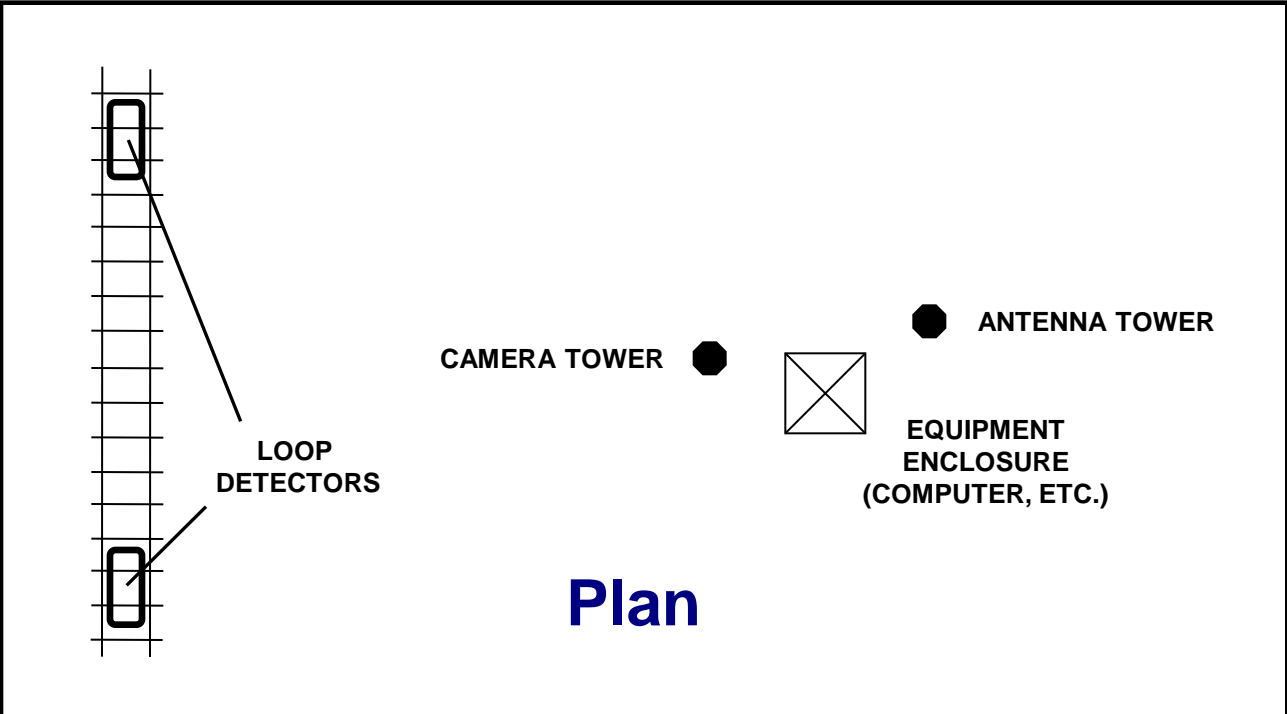


Automated Monitoring System at BNSF's Logistics Park Chicago Facility

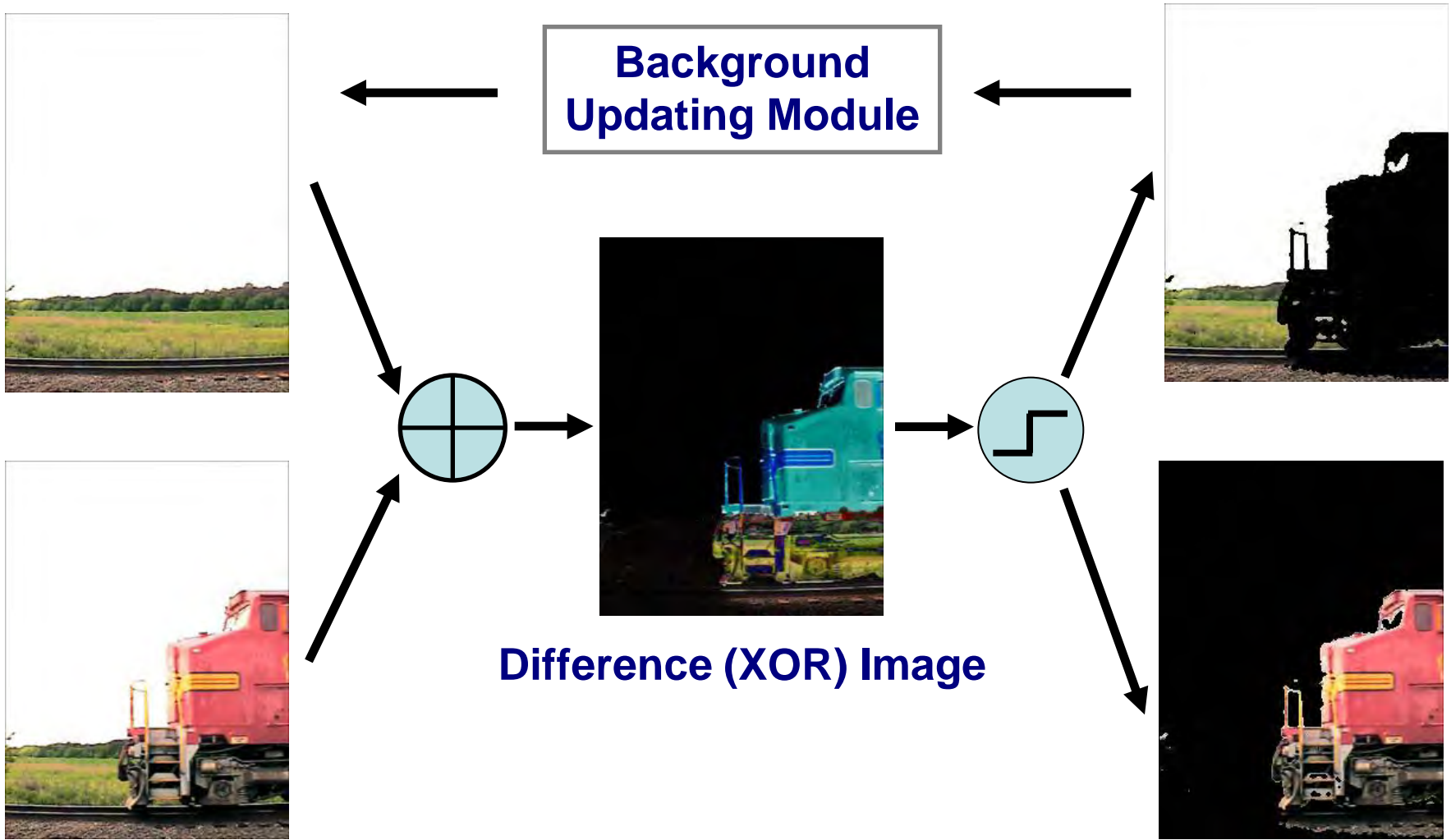


BNSF Logistics Park
Elwood, IL

Support Equipment Layout



Background Subtraction and Update Model

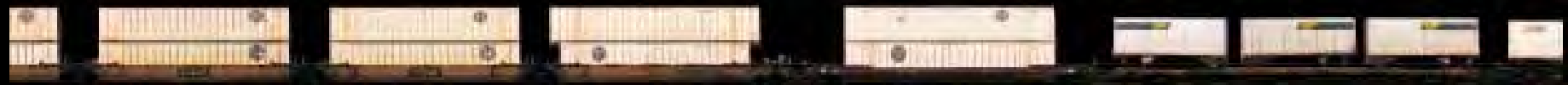
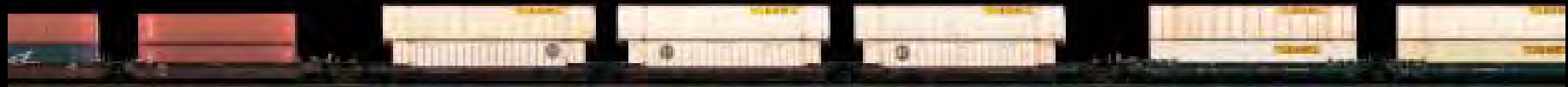


Panorama Image Generation



- The middle section of every frame in the video contributes to the construction of the panorama
- The panorama is constructed, a patch at a time, using each frame's central patch and its pixel velocity relative to the frame before

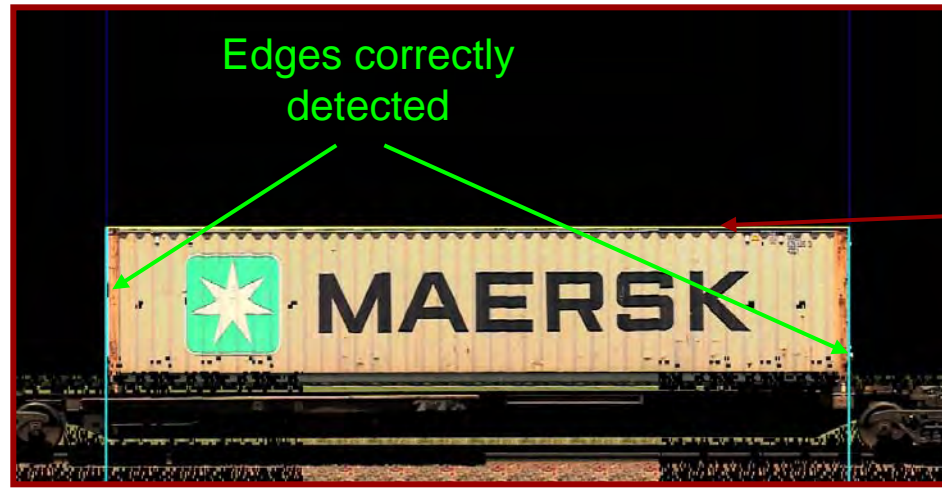




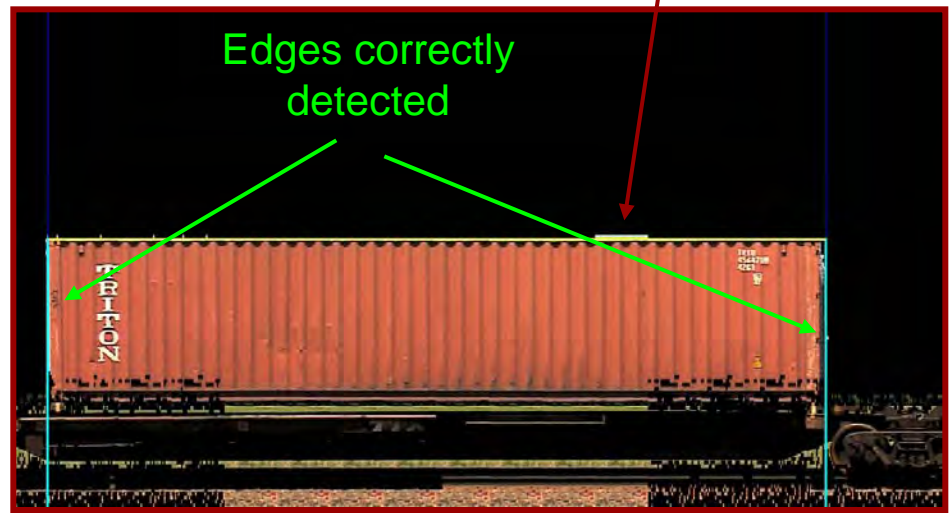
Processed Train Panorama



Results: Detection of Single Stack



Single Stack
Correctly
Detected



Results: Detecting Double Stacks



Double Stack Correctly Detected



Results: Detection of Trailers



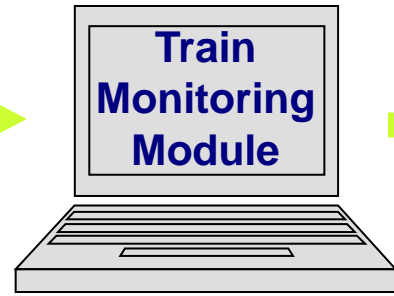
Trailers
Correctly
Detected



Evaluation of Loading Efficiency



Train Video



Train Panorama Reconstruction From Input Video with Identified Gaps and Detection of Containers/Trailers



Data Analysis System

- Edge detection and gap width data are matched with AEI equipment type data and also with timestamp data
- The aerodynamic efficiency of each train is calculated and a score is given to its loading pattern
- A report detailing the loading efficiency can then be developed and sent to the appropriate personnel

