Optimizing the Aerodynamic Efficiency of IM Freight Trains




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BNSF RAILWAY

ILLINOIS RAILROAD ENGINEERING PROGRAM

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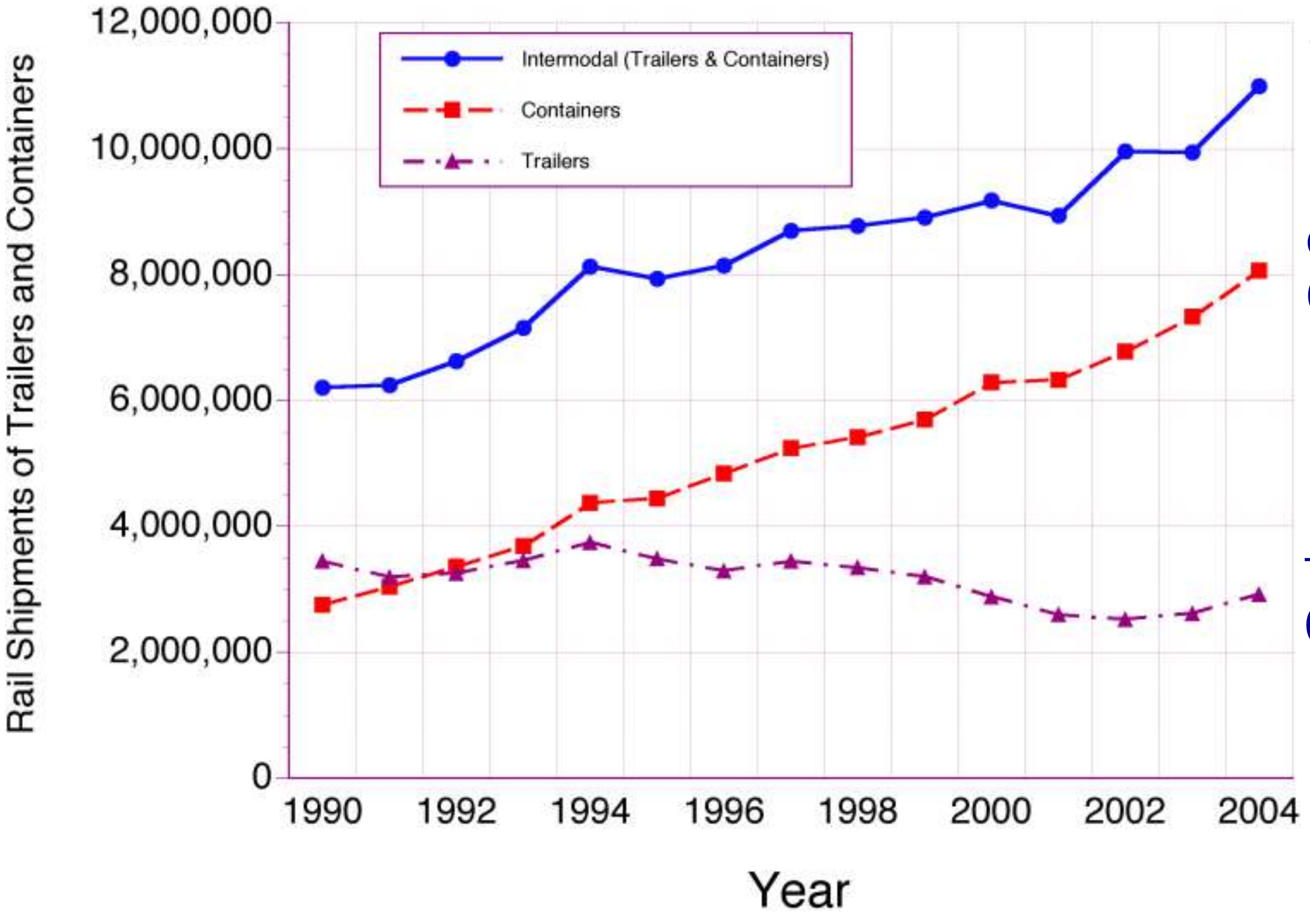
Intermodal traffic had increased 77% since 1990

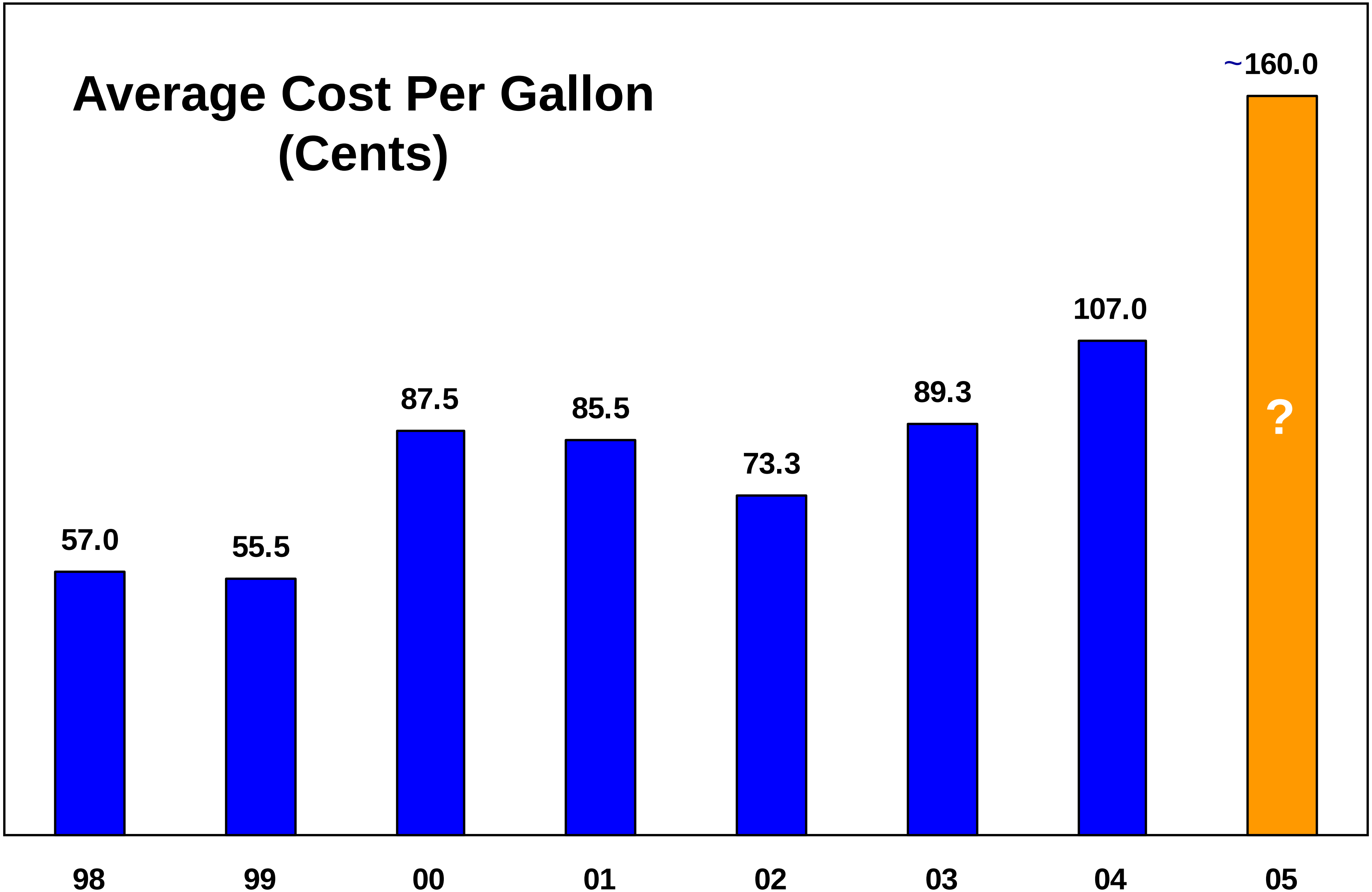


Total
(77% increase)

Containers
(193% increase)

Trailers
(15% decrease)

As of 2004, fuel costs had increased by more than 88% since 1998



Intermodal (IM) trains incur greater aerodynamic penalties and fuel consumption than general trains

IM trains suffer from their equipment design and loading pattern

These large gaps directly affect the aerodynamic drag of the train. This effect is greater at higher speed

It is thus ironic that IM trains are the fastest freight trains operated in North America

Consequently, we undertook an investigation of options to improve IM train loading and fuel efficiency

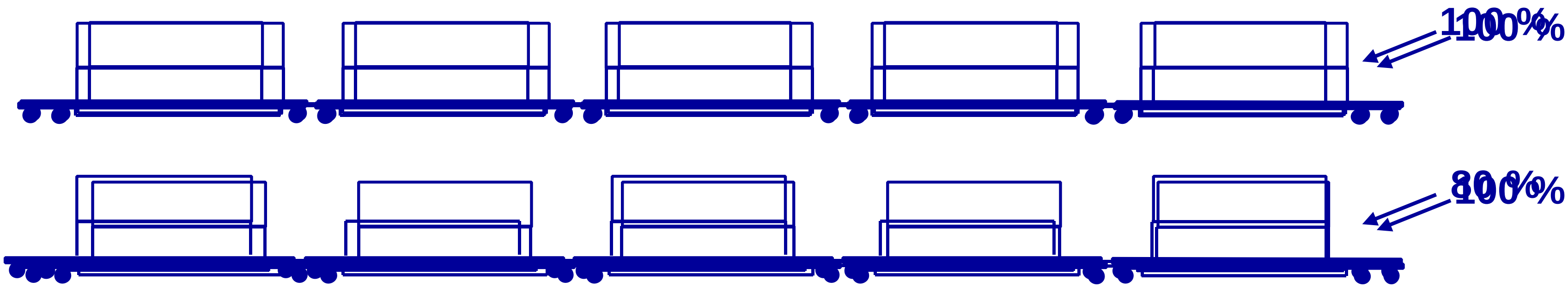
Loads should be assigned not only based on “slot utilization” but also “slot efficiency”

Slot utilization: a metric used to measure the percentage of the spaces (a.k.a. slots) on intermodal cars that 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



Train resistance is used for efficiency analysis

Train Resistance:

- General Train Resistance Equation:

$$R = \boxed{A} + \cancel{BV} + \boxed{C}V^2$$

TEM **AERO**

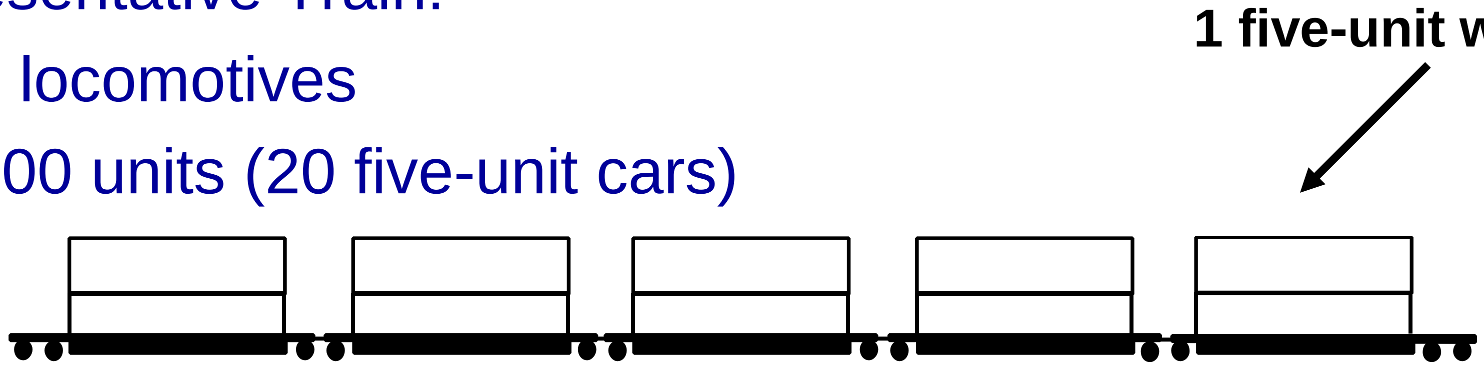
- Resistance model used in this study:

$$R = R_{BK} + R_{RK} + CV^2$$

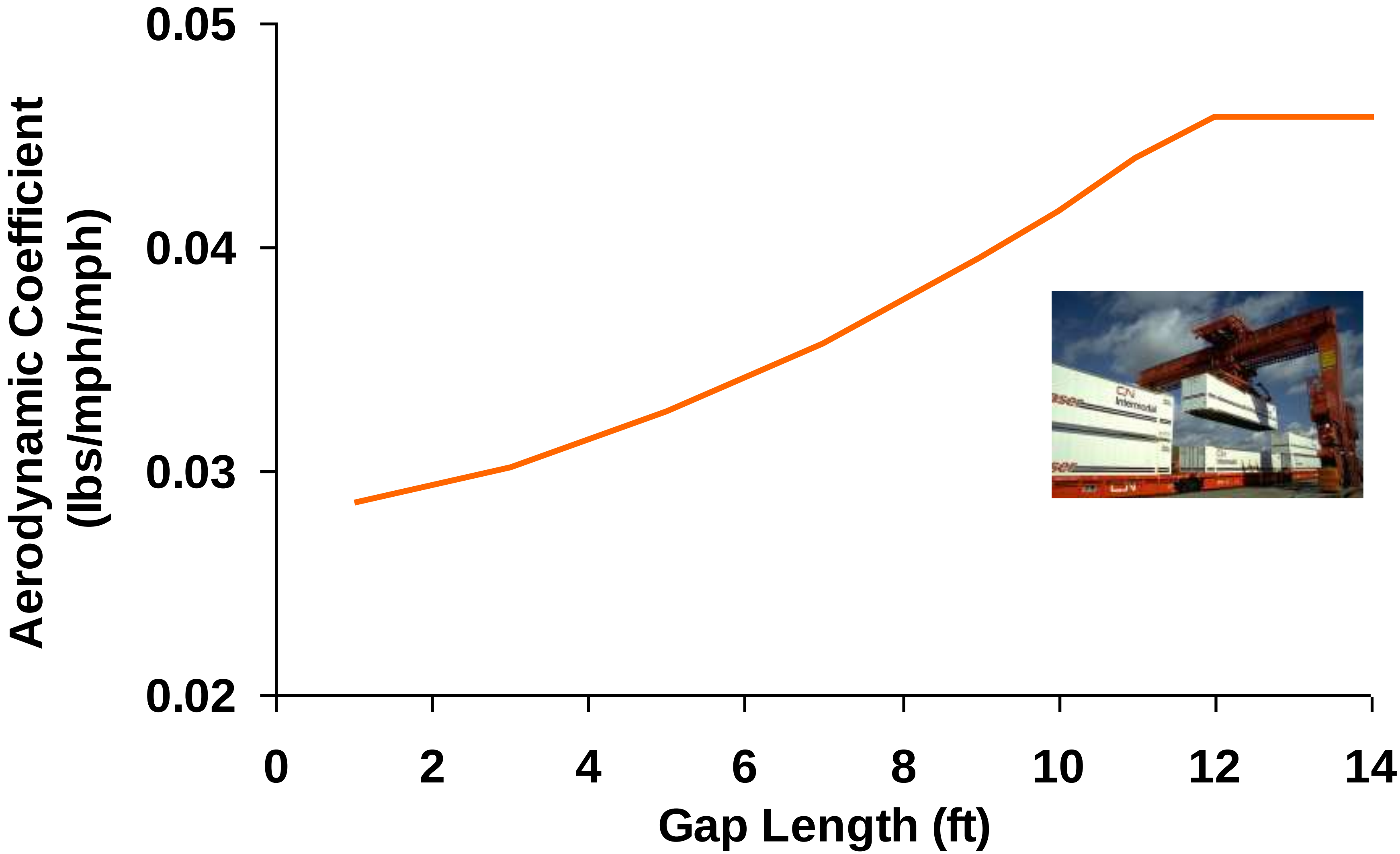
Fuel Consumption: AAR Train Energy Model (TEM)

Representative Train:

- 3 locomotives
- 100 units (20 five-unit cars)



Larger gaps resulting in a higher aerodynamic coefficient and greater resistance



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

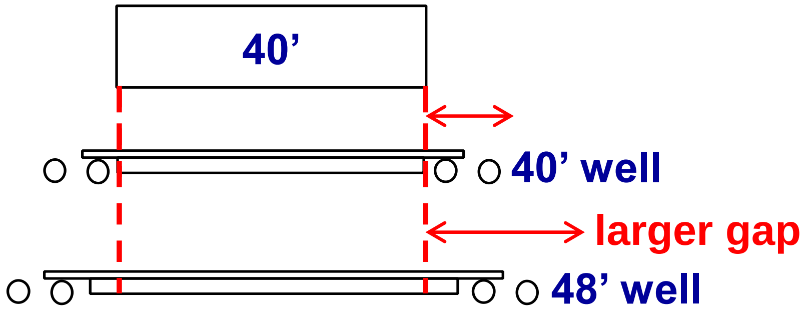
The capacity of well and spine cars is usually constrained by the length of the loads

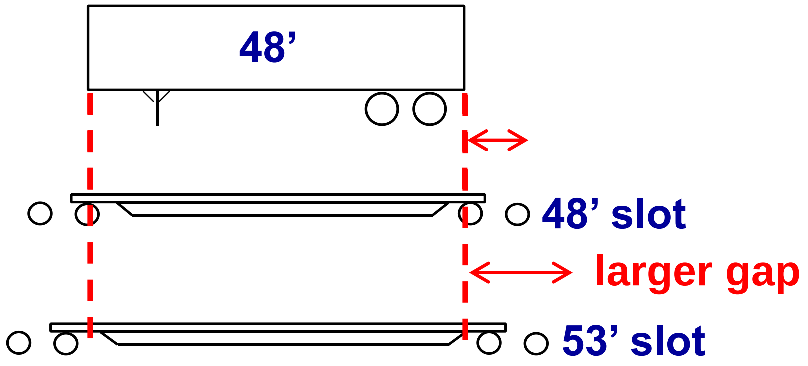
Equipment matching matches IM loads so as to minimize gaps

Example:

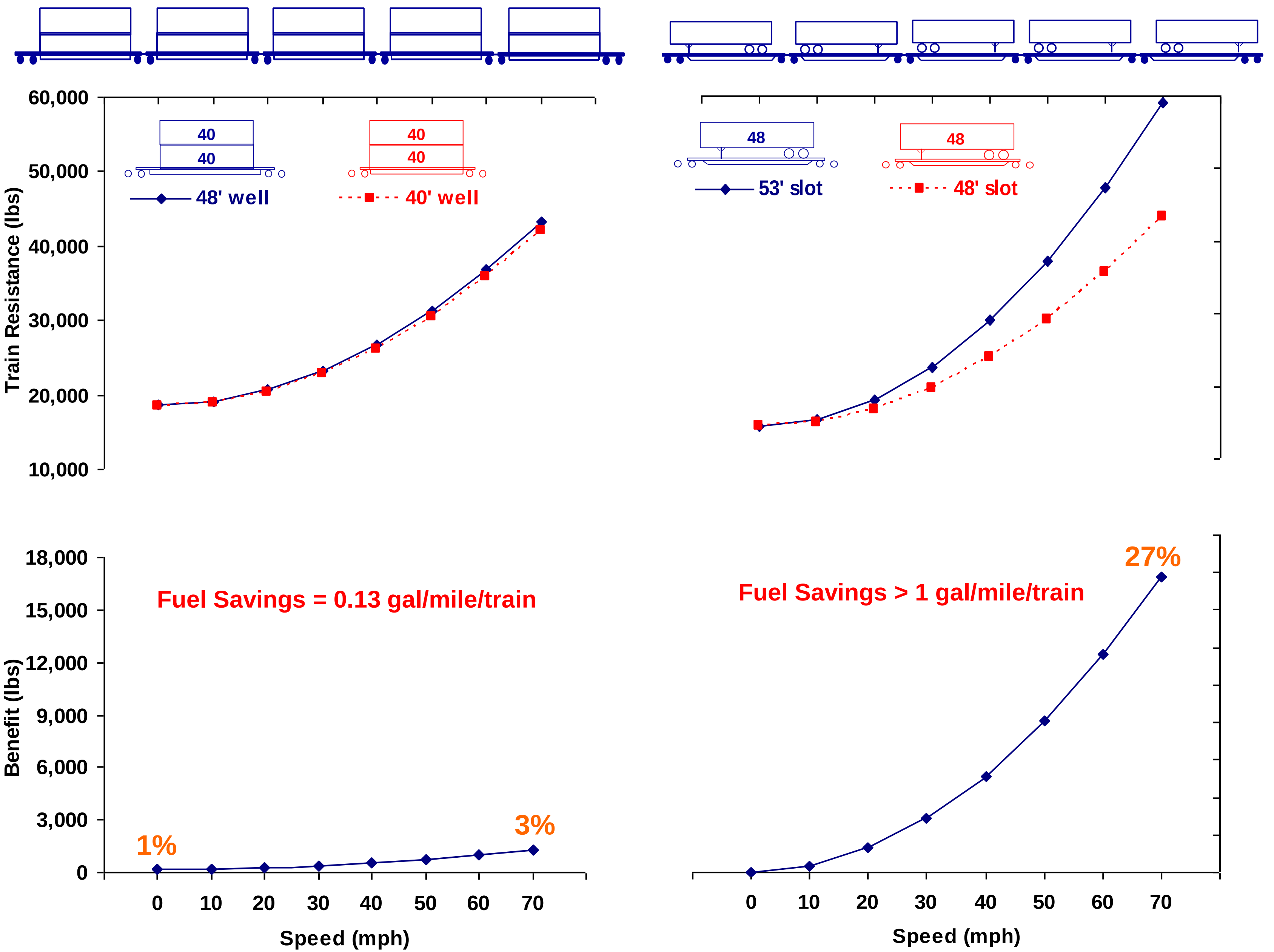
- 40' container in 40' well car, rather than a 48' well car

- 48' trailer in 48' slot spine car, rather than car with 53' slot

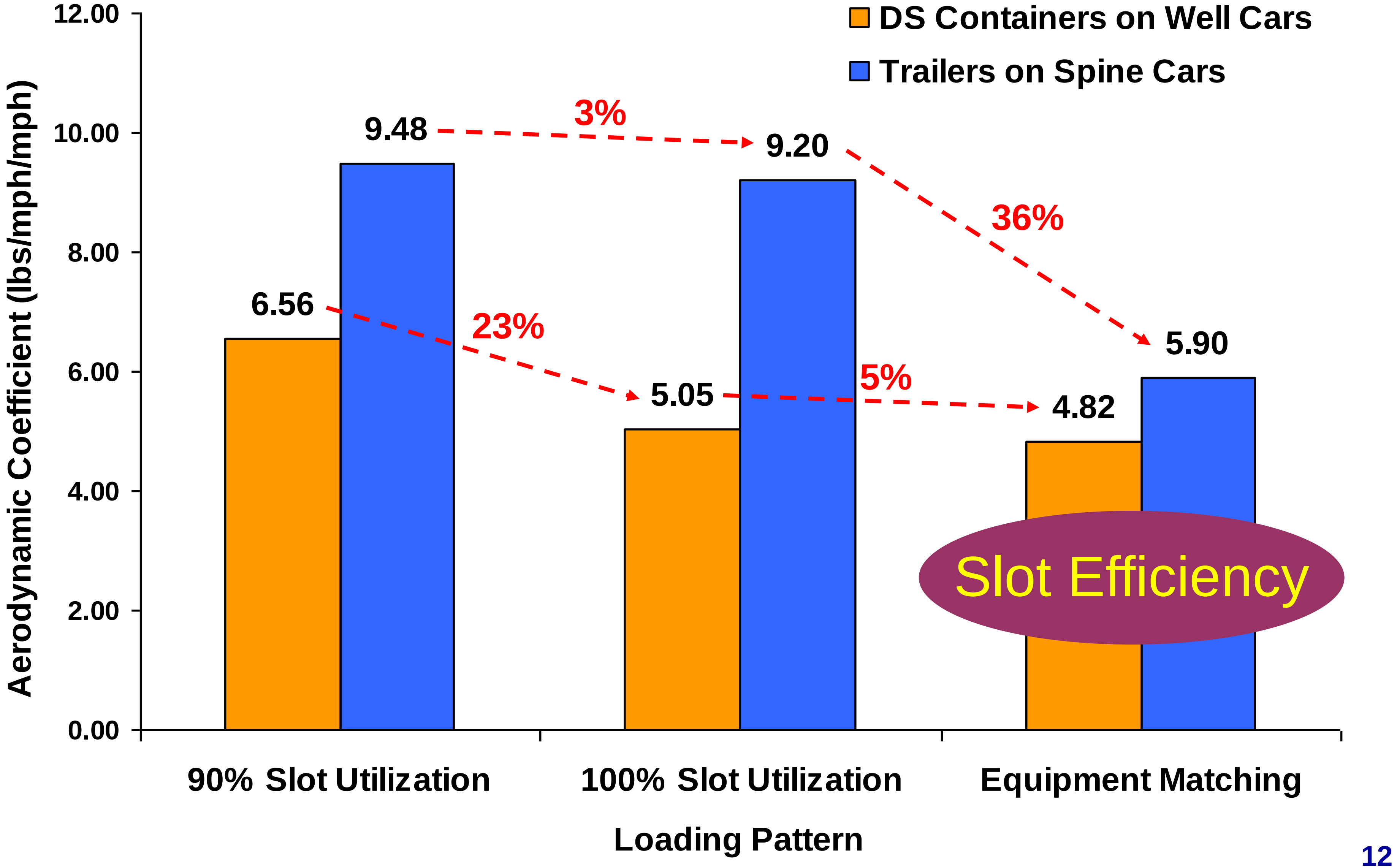




Matching can save fuel by as much as 1 gal/mile



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



A model to automatically assign loads to the train ensuring minimum fuel consumption is needed

At IM terminals, terminal managers often use computer software as decision making tools to comply with loading assignment rules

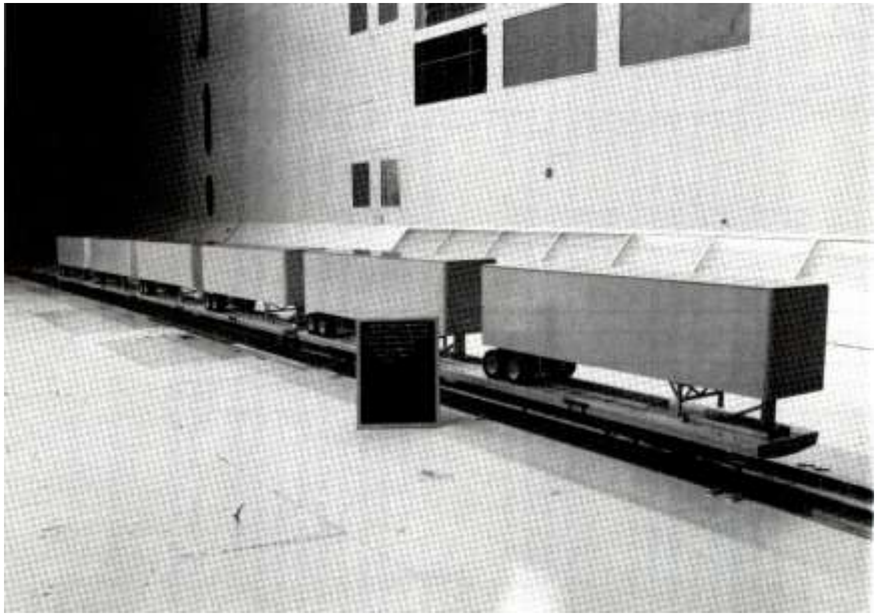
However, loading assignment is still a largely manual process

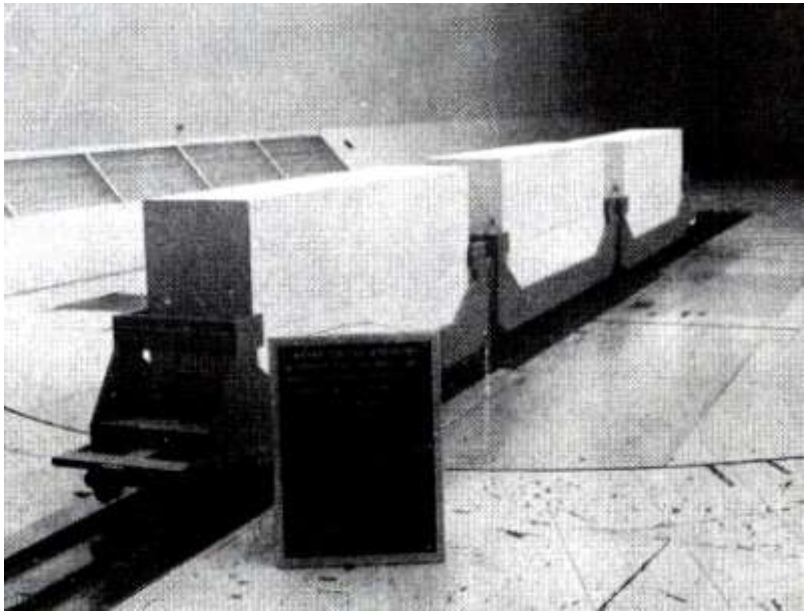
Because cars in an IM train generally are not switched, managers primarily control the assignment of loads but not the configuration of the cars in a train

The current goal of loading is to reach the highest possible slot utilization

Although perfect slot utilization indicates maximal use of spaces available, it does not ensure that IM cars are loaded to maximize the 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)

The front of the train experiences the greatest aerodynamic resistance

$$C_D A(ft^2) = 14.85824e^{-0.29308k} + 9.86549e^{-0.00007k} + 10.66914$$

Unit (k) #	Drag area (C_DA) (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

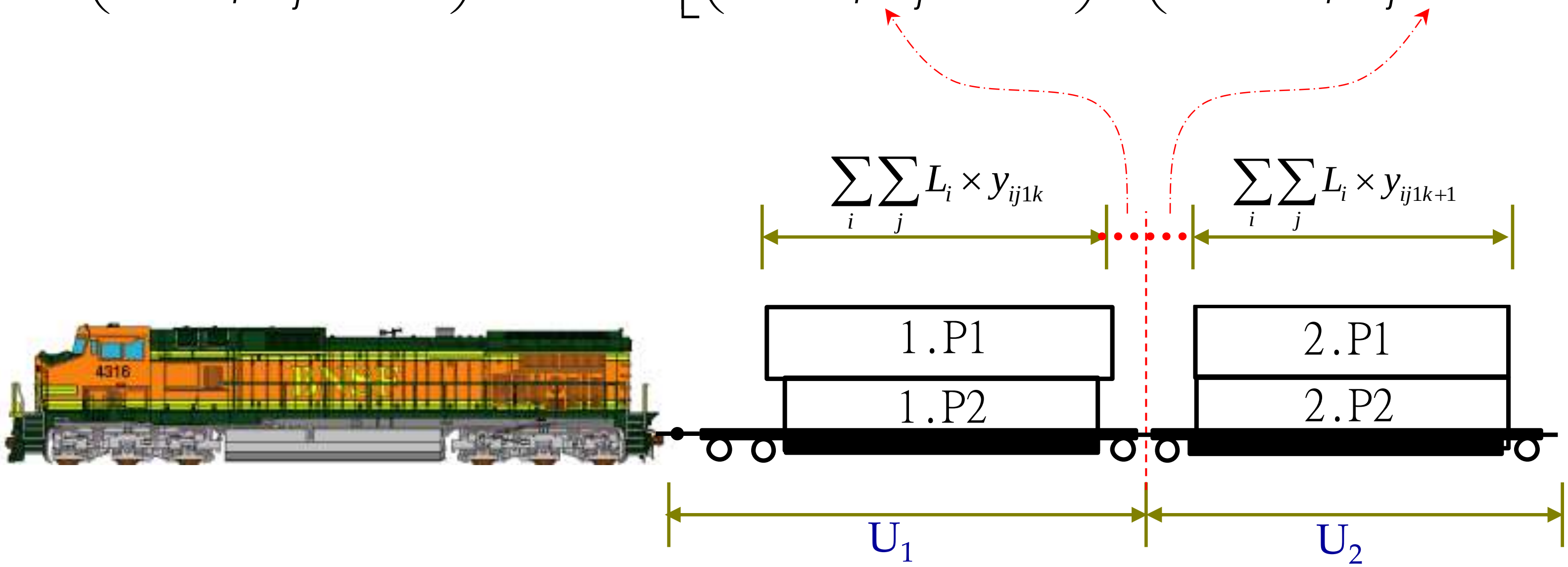
Objective:

Minimize the total "adjusted" gap length within the train

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

Z is the total "adjusted" gap length within the train

$$z = \frac{A_1}{2}\left(U_1 - \sum_i \sum_j y_{ij11} L_i\right) + \frac{\sum_{k=1}^{N} A_{k+1}}{2}\left[\left(U_k - \sum_i \sum_j y_{ij1k} L_i\right) + \left(U_{k+1} - \sum_i \sum_j y_{ij1k+1} L_i\right)\right]$$



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

Minimizing the total adjusted gap length within the current outgoing train

Min Z

Subject to:

$$\left.\begin{aligned}&\sum_{p}\sum_{k} y_{ijpk} R_{ipk} \leq 1 \quad \forall i, j\\ &y_{ijpk} \leq R_{ipk} \quad \forall i, j, p, k\end{aligned}\right\}\ \text{Loading capabilities}$$

$$\left.\begin{aligned}&40 - \sum_{i \in C}\sum_{j} y_{ij2k} L_i \leq \Phi(1 - x_k) \quad \forall k \ (\text{such that } \delta_k = 1)\\ &\sum_{i \in C}\sum_{j} y_{ij1k} \leq x_k \quad \forall k \ (\text{such that } \delta_k = 1)\end{aligned}\right\}\ \text{double-stack rules}$$

$$\sum_{i}\sum_{j}\sum_{p} y_{ijpk} w_{ij} \leq C_k \quad \forall k \quad \longleftarrow \text{weight constraint}$$

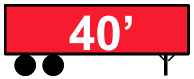
$$\sum_{i}\sum_{j} y_{ijpk} L_i \leq Q_{kp} \quad \forall k, p \quad \longleftarrow \text{length constraint}$$

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

Where:

- R_{ipk} = Loading Capability
- w_{ij} = Weight of j^{th} Load in i Type
- C_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

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

Loads: fifty 

, fifty 

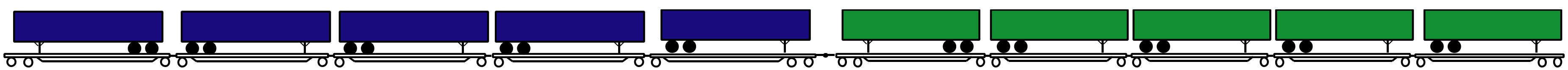
, fifty 

150 loads

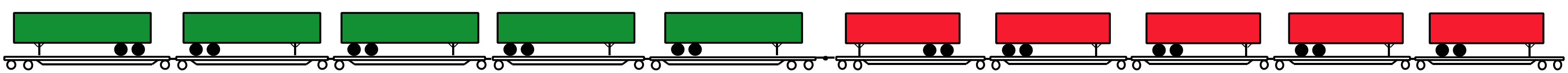
Train: ten 5-unit 53-foot-slot spine cars followed by
ten 5-unit 48-foot-slot spine cars

100 slots

Optimum based on IP = 514 (ft)

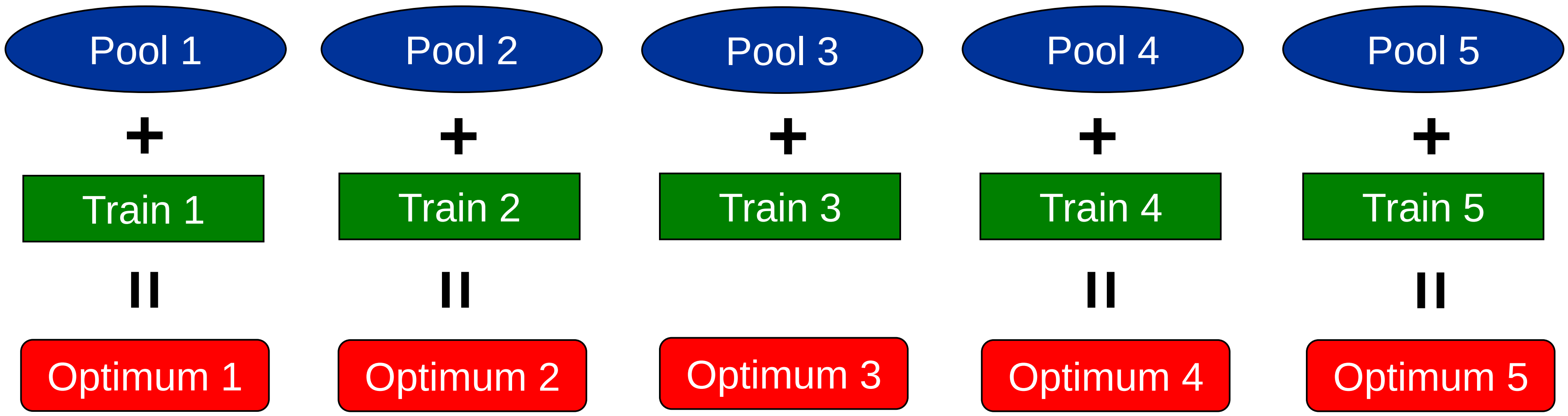


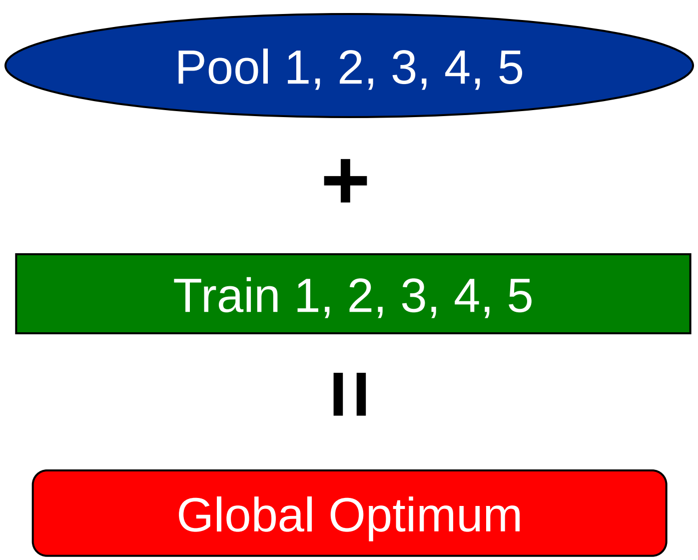
Worst case by manual assignment = 1170 (ft)



Fuel savings is 0.95 gallons/mile/train

Can we do more?





This increases the flexibility both in the pool (loads) and trains

Optimizing more trains and loads together will lead to more efficient loading pattern

Static Aerodynamic Efficiency Model minimizes the total "adjusted" gap length of multiple trains

Min $\sum_{t=1}^{T} z_t$

Subject to:

$$\left.\begin{aligned}&\sum_t \sum_p \sum_k y_{ijtpk} R_{itpk} \le 1 \quad \forall i, j\\ &y_{ijtpk} \le R_{itpk} \quad \forall i, j, t, p, k\end{aligned}\right\} \text{Loading capabilities}$$

$$\left.\begin{aligned}&40 - \sum_{i \in C} \sum_j y_{ijt2k} L_i \le \Phi(1 - x_k) \quad \forall t, k \ (\text{such that } \delta_k = 1)\\ &\sum_{i \in C} \sum_j y_{ijt1k} \le x_{tk} \quad \forall t, k \ (\text{such that } \delta_k = 1)\end{aligned}\right\} \text{double-stack rules}$$

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$$\sum_i \sum_j y_{ijtpk} L_i \le Q_{tkp} \quad \forall t, k, p \longleftarrow \text{length constraint}$$

$$y_{ijtpk}\ ,\ x_k = 0,\ 1$$

Where:

- R_{itpk} = **Loading Capability**
- w_{ij} = **Weight of j^{th} Load in i Type**
- C_{tk} = **Weight Limit of k^{th} Unit**
- Q_{tkp} = **Length limit of position p in k^{th} Unit**
- δ_{tk} = **1 for well-car unit; 0 otherwise**
- Φ = **a large positive number**
- x_{tk} = **1 if the top slot of k^{th} Unit can be used; 0 otherwise**

t = Train index (1,2,…, T)

There is a trade-off between optimizing multiple trains together and risk of making wrong decisions

Optimization of multiple trains is beneficial if complete information on trains and loads is available

However, in practice, loads come and go at the terminal in very short amount of time

Therefore, optimizing the loading pattern of a later train may reduce the efficiency of the immediate outgoing train

This uncertainty about future loads introduces some degree of risk that the overall optimum will not be achieved

Dynamic Aerodynamic Efficiency Model balances short-term versus long-term efficiency

Min $\sum_{t=s}^{s+\tau} \alpha_{s,t} z_t$ subject to the same constraints

$\tilde{\alpha}(s)$ = (1, α_s, α_s^2, …) for $0 < \alpha_s < 1$.

a weighted average of short-horizon and long-horizon objectives

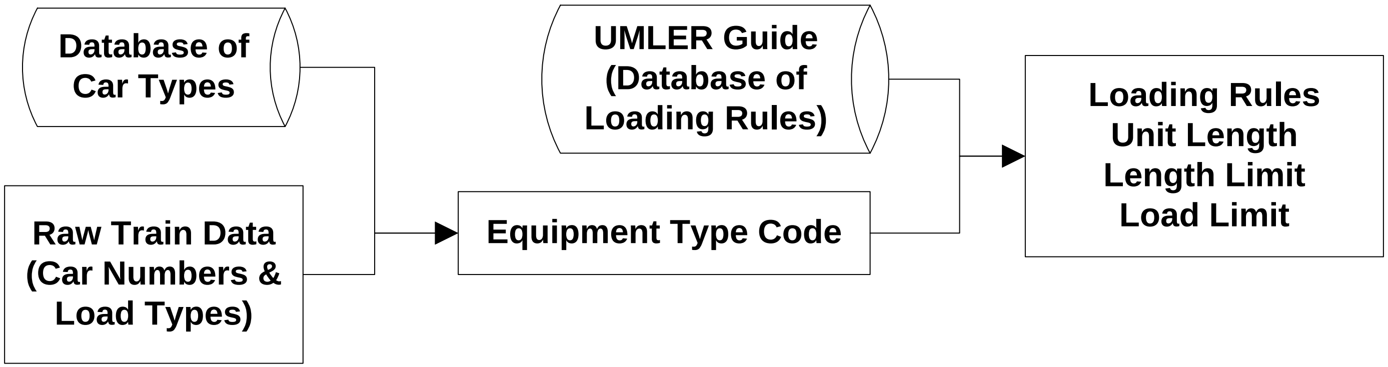
Where:

τ = Maximum number of future trains can be filled with current available loads

$\alpha_{s,t}$ = Additional weight assigned to a future train $t \geq s$

The modification of the objective function has been shown to improve the optimal solution by balancing short-term versus long-term loading efficiency

Six mixed trains in 8-hour window are selected for empirical case study

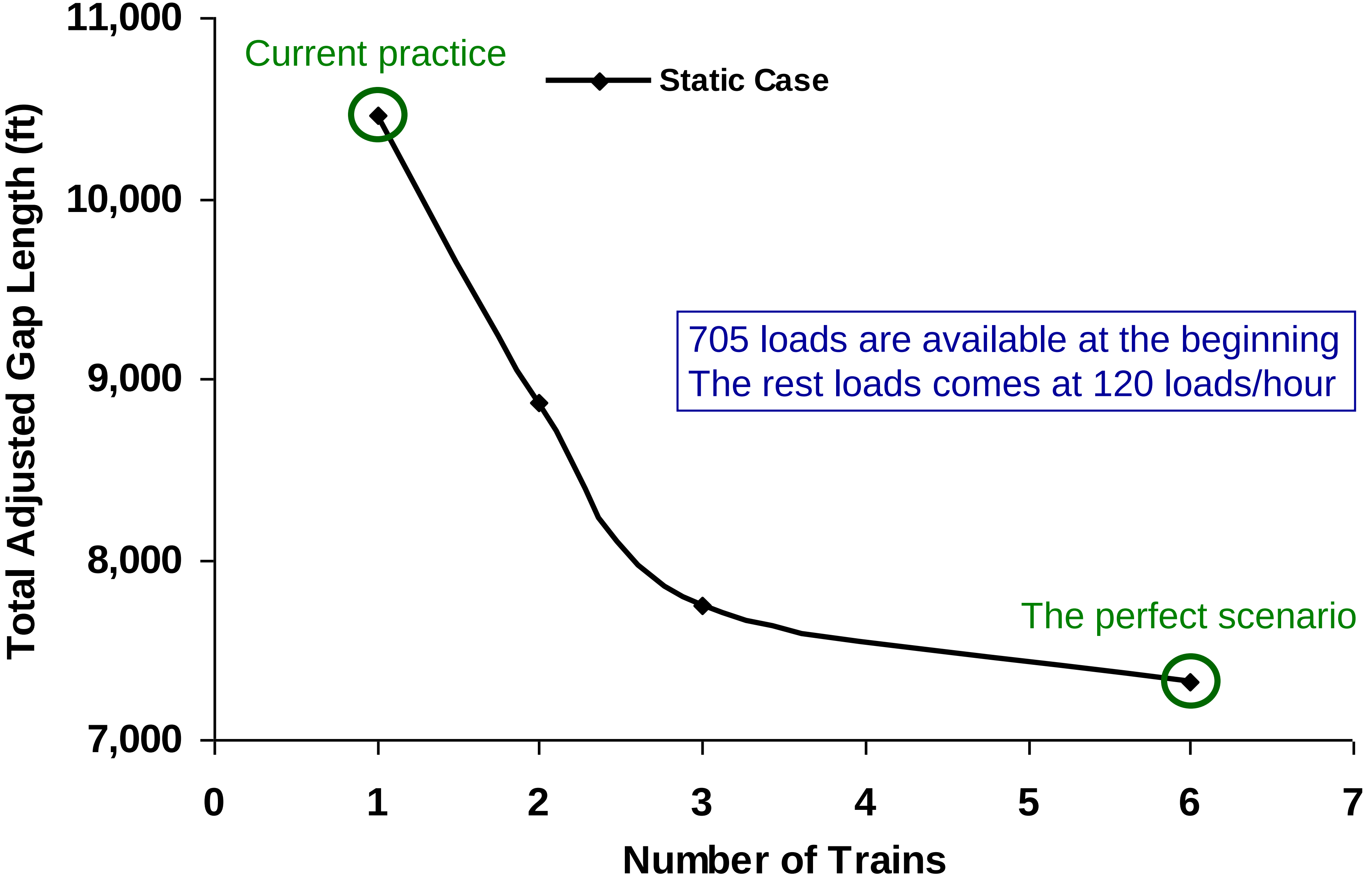


The data were received for BNSF Railway – Chicago to LA trains on December 4th, 2005

There are 6 trains and 1,380 loads to be optimized:

1. Q-CHIRIC6-03A (All wells: 31 Railcars)
2. S-CHILBP1-03A (All wells: 27 Railcars)
3. Q-CHILAC1-03A (Mixed: 39 Railcars)
4. S-CHIOIG1-03U (All wells: 30 Railcars)
5. Q-CHIALT3-03A (Mixed: 36 Railcars)
6. Q-CHISBD3-04A (Mixed: 42 Railcars)

A rolling horizon framework is proven to be suitable for continuous terminal operations



The output of rolling horizon 22% better than the current manual assignment

The proposed loading assignment model shows a substantial benefit from optimizing the aerodynamic efficiency of IM trains

Extrapolating the savings over the BNSF Chicago-LA route (2,200 miles) can be 1,500 gal/train

Since using the dynamic model is even more beneficial, the necessary additional planning or handling may be worthwhile

The loading assignment model can be integrated into terminal operation software to help managers make the best decisions