Train energy, power and traffic control

Q1: What is objective of a rail transportation system?

A1: To provide **TRANSPORTATION**! (freight and/or passenger)

Q2: What are the principal factors affecting the capacity of a rail system to provide transportation?
Railway Elements Affecting Transportation Capacity

ALMOST EVERYTHING!

Railroad Network
System operation affects efficiency and service reliability

Line & Terminal Operation
Timely and efficient train operation and use of equipment & personnel

Traffic Control System
Safe, efficient operation of many trains on same tracks

Rail Cars
Design and size affect operating efficiency

Locomotive
Efficient conversion of energy into tractive force to pull train

Brake System
Safe stopping distance affects train spacing and line capacity

Track System
Structure & condition affects speed and maintenance requirements

Wheel/Rail Interface
Complex dynamics affect stability & speed
Comparison of truck vs. rail energy efficiency

What distance can each mode transport a given amount of freight for a given amount of energy?

i.e. how far can we transport one ton of freight with one gallon of diesel fuel?

Rail is over 3 times more efficient than truck

(AAR & FRA data)
Why?

• What are the two primary aspects of transportation energy efficiency?
  – Resistance
    How much work is required to move something.
  – Energy efficiency
    How efficiently energy is converted into useful work.
What is resistance and how is it measured?

If this weight $w$ is sufficiently heavy to overcome the combined rolling and axle friction, the car will commence to move.

Resistance is typically measured in “pounds per ton” (in U.S.)

Early measurement of railcar resistance simply involved piling weight on at $w$ and determining how much was needed to make the car move.

Same basic concept applies to measuring resistance in any other transport mode, although the effect of speed is not accounted for by this method.
Rail uniquely combines **High Speed** and **Low Resistance**.

Modified from Hay "Transportation Engineering"
Trains require less force to move than trucks

- What are the principal reasons?
  1) Steel wheel on steel rail has much lower rolling resistance than rubber tire on pavement.
  2) Stronger vehicles and infrastructure allow heavier loads, thereby allowing economies of scale (ca. 3 x truck).
  3) “Trains” - multiple, closely-coupled vehicles are more aerodynamic, and experience less air resistance per railcar than trucks.
Sources of rail vehicle resistance

A = resistances that vary with axle load (includes bearing friction, rolling resistance 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
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, it is still sometimes referred to as the “Davis” equation.

• \[ R_o = 1.3 + 29/w + bV + CAV^2/wn \]

where:

\[ R_o = \text{resistance in lbs. per ton} \]
\[ w = \text{weight per axle (}= W/n) \]
\[ W = \text{weight of car} \]
\[ b = \text{an experimental friction coefficient for flanges, shock, etc.} \]
\[ A = \text{cross-sectional area of vehicle} \]
\[ C = \text{drag coefficient based on the shape of the front of the train and other features affecting air turbulence etc.} \]

• The Davis Equation has been substantially updated to reflect modern developments, but its basic form is the same.
At low speeds, journal resistance dominates, but as speed increases air resistance is increasingly the most important term.
Resistance versus speed for a 10,000 ton train

- Train resistance is calculated by multiplying the resistance per ton at each speed, by the total tonnage of the train.
Q: How do railroads overcome such large resistances?
Physics of power, force and speed

- Work = force x distance \( W = F \times D \)
- Power is the rate at which work is done
  \[ \text{Power} = \frac{\text{work}}{\text{time}} \quad P = \frac{W}{T} = \frac{FD}{T} \]
- The relationship between Force and Distance/Time (i.e. speed) is thus inverse
- The higher the speed, the less force available
- Curves like this are used to describe the performance capabilities of locomotives
Typical modern freight locomotive

6,000 horsepower, 212 tons

Typical modern freight train

100 cars x 143 tons each = 14,300 tons
Speed/tractive effort curve for a modern locomotive

At low speed, tractive effort is limited by adhesion, not power

Tractive effort is measured in pounds of force available as a function of speed
Train resistance and tractive effort are both measurements of force (typically in pounds in North America) so we can simply overlay the curves.

Q: What is the maximum speed possible for this train with this locomotive?
A: About 58 mph. This is referred to as the “balancing speed”.

Tractive force = resistance ca. 35,000 lbs.
The difference between tractive effort and resistance is the force available for acceleration.

Force available for acceleration declines with speed until the balancing speed is reached, where it is zero. Consequently, the rate of acceleration declines with speed.

Q: How much force is available for acceleration at 15 mph?
A: $135,000 - 15,000 = 120,000$ lbs.

Q: How much force is available for acceleration at 35 mph?
A: $59,000 - 21,000 = 38,000$ lbs.
Multiple unit control

• Nearly all modern locomotives (electric and diesel electric powered) are capable of “multiple unit” control
• The control circuits can be electrically connected so that a single operator can control multiple locomotives
• This allows power to be matched to the requirements of any size train to maximize either efficiency or speed
• This concept has been extended through the use of radio-controlled “slave” units distributed through the train.
• “Distributed power” is particularly useful for heavy freight trains because it enables longer trains and better control, particularly on grades.
Two units, double the power

Capability of “multiple unit” control makes this possible
Freight Train Time-Speed Graph

This curve depicts a single locomotive, how will the curve change if a second locomotive is added?

How long will it take for this train to reach 40 mph?
About 900 seconds = 15 minutes
Now how long will it take to reach 40 mph?
About 300 seconds
≈ 6 minutes
Freight Train Distance/Speed Graph

How many miles until this train reaches 40 mph?
About 75,000 feet
= 14 miles
With 2 locomotives, only about 25,000 feet ≈ 5 miles
Horsepower to trailing tonnage ratio for different types of trains

- General merchandise or “manifest” freight train
  - Low horsepower:trailing ton ratio
    12,000 hp: 14,300 tons = 0.83 hp:ton

- High-speed train, especially if there are frequent stops and starts.
  - High horsepower:trailing ton ratio may be 2 to 4 hp:ton
  - Typical of “hot” intermodal trains and is even higher for passenger trains
Highest horsepower to trailing ton ratio

BNSF Fast UPS test train
= 6 hp:trailing ton

Conventional passenger train
= 4 to 8 hp:trailing ton

Rapid transit
= 10 hp:ton
Time/distance graph
freight train with one locomotive
Stopping the train

• From a safety standpoint, stopping the train is even more important than accelerating it.

• The same low coefficient of friction between steel wheel and steel rail that allows low rolling resistance, also limits braking ability.

• Although trains can be decelerated in less distance than they can be accelerated, stopping a train requires considerably more distance and time than a motor vehicle.
Stopping a train can often take a mile or more.
Railroad grade crossings

- Laws of physics dictate that a train cannot stop if a motor vehicle is on the tracks at a highway rail grade crossing.
- Therefore, protection of grade crossings is critically important.
- Motorists must observe and respect warning systems.
Key differences between railroad and motor vehicle traffic control

• Safe stopping distance of a train is considerably greater than that of a motor vehicle.

• Stopping distance frequently exceeds sight distance.

• Trains operate on a “fixed guideway” or “single-degree-of-freedom” system.
  – Train operator cannot alter the train’s course to avoid a collision.

• This photograph is the view that an operator of a German high-speed rail passenger train has. Train speed may exceed 150 mph. If there is another train stopped on the track ahead, how is the operator to know in time to stop the train? Requires different type of traffic control system than motor vehicles.
Simple possible solution

- Allow only one train on a track at a time
- By controlling access, i.e. by “granting authority” to a train to use a section of track, a dispatcher can ensure that there are no collisions
- Will this work?
  - Yes
- What are the drawbacks?
  - Inefficient use of infrastructure
- When might a system like this be suitable?
  - Low density line
What if there is more traffic, and line capacity needs to be increased?

• How can the capacity of a line with a traffic control system such as this be increased?
  – divide it up into “blocks”

• Train dispatcher can ensure that there are no collisions by controlling access to each block.

• Allows more trains to operate on the line simultaneously

• These systems employed people as “block operators” who worked in “block stations” located every few miles along the rail line
Safe stopping distance

- Remember, trains cannot stop quickly, so in the simplest manual block system, trains had to approach each block station prepared to stop, in case another train was just ahead.
- Inefficient - particularly when one considers the time and energy required to accelerate the train each time it stops.
- Need some system of advance notice to trains if they need to stop or not.
“Home” and “Distant” signals

• **Good Solution:**
  “Home Signal” that train crew can see before they arrive
  
  These were mounted along side the track at each block station

• **Better solution:**
  Add a “Distant Signal” that tells crew whether they need to stop or not at the next “Home Signal”.
  
  These were located some distance ahead of the block station and the Home Signal and provided advance notice of its status.
Manual Block Signal Control

Note: Block signals shown in one direction only for clarity

Home Signal – Block Station A
At points where distant signal is not provided, trains must approach each block station prepared to stop short of entrance to block.

Starting distance from maximum authorized speed

Distant Signal for Block Station A

Block Station B

Approach – (Home signal at Stop)

Stop – Block Occupied

Proceed – Block Unoccupied

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Direct Traffic Control

Dispatcher at remote location

Similar to Manual Block, except block stations and operators replaced by a single dispatcher using radio instead of wayside signals to monitor train position and communicate block occupancy status.
Q: What are the drawbacks of the manual block system?

A: It is labor intensive

Ideally we would have an automatic system for railway traffic control. How could one do that?
Basic railway track circuits

Track is unoccupied, track relay is energized, circuit is shunted to illuminate **Green** indicating “clear”

Track is occupied, wheel & axle shunts track circuit, de-energizing track relay, circuit is shunted to illuminate **Red** indicating “stop”

The rails conduct low voltage electric current and the track is divided into electrically isolated “blocks”. As train moves from block to block its presence is detected. The system is “Fail Safe”, that is, if it fails it is in the most restrictive condition. This includes failed track battery, broken wires or a broken rail in the block.
Automatic block signals

Note: Block signals shown in one direction only for clarity
Centralized Traffic Control

- A system by which the movement of trains over routes and through blocks is directed by signals controlled from a designated point without requiring the use of train orders and without the establishment of the superiority of trains.

- A term describing the system that provides an economical means for directing the movement of train by signal indications without the use of train orders.

- A combination of automatic block systems and interlockings which can be adapted to any existing signal indication and applied to single track or to two or more tracks.
Example CTC Display
Positive Train Control (PTC)

Coming soon to a railroad near you!

Computer-Aided Dispatching
- Performed the same as today
PTC Background

• Rail Safety Improvement Act of 2008 mandates installation of positive train control (PTC) on:
  – All mainlines over which operate regularly-scheduled commuter or intercity passenger trains
  – Mainlines of Class I freight carriers over which Toxic Inhalation Hazardous (TIH) materials are handled
  – Such other lines as designated by the Secretary of Transportation
PTC and CBTC

• **Positive Train Control (PTC)** is a system designed to prevent:
  1. Train-to-train collisions
  2. Over-speed derailments
  3. Incursions into established work zone limits
  4. Movement of a train through a switch left in the wrong position

• **Communications Based Train Control (CBTC)** is a **control system** in which train monitoring and train control are integrated into a single system via data links between vehicle, central office and wayside computers
PTC vs. CBTC

- **PTC** is a performance standard based on legislation and regulation
- **CBTC** is a train control technology
  - CBTC may not meet PTC requirements
  - PTC requirements can be met without CBTC
- Current proposals are for PTC qualified CBTC systems
A Review of Current Traffic Control Systems

• Authority transmitted via:
  – Written or verbal messages
  – Wayside signals
• Wayside signals *manage* speed and headway
• Trains are separated by a distance several times their stopping distance
Real Time Train Speed and Location Data

- Information for dispatcher:
  - Allows train dispatchers to respond more quickly to changing conditions and service disruptions
  - Can improve meet/pass planning

- Information for train crew:
  - Provides real-time data on authorities, train spacing and route
  - Engineer is able to receive and react to changing signals and authorities immediately
Moving Blocks

- Enables train separation to based on the stopping distance and speed of the individual train

3-Aspect Conventional Signal System

- Minimum Headway at Normal Speed
- Start of Braking

Standalone CBTC with Moving Blocks

- Start of Braking/Minimum Headway
Benefits of Moving Blocks

• Reduce time lost during passes on single track
  – Shorter headways and eliminates time waiting for first block to clear
• Heterogeneous traffic
  – Train separation based on individual train characteristics
• Temporary track outages
  – Fleeting possible with closer headways
• However implementation requires a suitable means of broken rail detection
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