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MEASURING THE IMPACT OF ADDITIONAL RAIL TRAFFIC USING HIGHWAY & RAILROAD METRICS

Samuel L. Sogin
University of Illinois
Urbana, IL, USA

Christopher P.L. Barkan. PhD
University of Illinois
Urbana, IL, USA

Yung-Cheng Lai. PhD
National Taiwan University
Taipei, Taiwan

Mohd Rapik Saat. PhD
University of Illinois
Urbana, IL, USA

ABSTRACT
Long term demand for freight movements in North America is expected to increase dramatically in the coming decades. The railroads are poised to take on this additional traffic assuming the capacity is available. Measuring the capacity of these rail lines is complicated by the interrelationships between asset utilization, reliability, and throughput. There is not a single metric that captures these intricacies. Capacity can be determined by delay-volume relationships, utility models, or economic study. For many case studies, railroads use parametric and simulation modeling to determine the train delay per 100 train miles. This metric does not tell the full story; especially when comparing different train types. The highway industry uses a different portfolio of metrics that can be adopted by railroad capacity planners. These metrics can be more sensitive to the worse performing trains. Additionally, these metrics can control for increased delay simply due to additional traffic. These concepts are illustrated by simulating the impact of additional 110 mph passenger service to a single track freight line.

INTRODUCTION
The North American railroad network is expected to experience continued growth in freight traffic. Overall freight demand is projected to increase 84% by 2035 [1]. New passenger services are being proposed to operate over portions of the freight railroad infrastructure. The freight railroads continue to invest in intermodal freight cars and terminals [2]. These faster train types have different characteristics in terms of acceleration, braking, top speed, priority and on-time performance. The impact of the new traffic can vary drastically based on the metrics used. Additionally, the term “capacity” can have different meanings to different stake holders.

There are many metrics used both by the railroad and highway industry to analyze and plan operations. A subset of these will be examined in this paper. Additionally, railroads and highways have certain key traffic relationships that will be compared. These metrics and traffic relationships are then illustrated by simulating shared corridor operations with freight and passenger trains.

TRANSPORTATION METRICS
There are four important definitions of railroad capacity as defined in a study conducted by Transport Canada in 1979 [3]:

1. *Practical Capacity*: Ability to move traffic at an “acceptable” level of service
2. *Economic Capacity*: The level of traffic at which the costs of additional traffic outweighs the benefits
3. *Engineering Capacity*: The maximum amount that can possibly be moved over a network
4. *Jam Capacity*: The system has ceased to function and all trains are stopped

The first and second definitions of capacity are the most relevant. Rail lines should continue to serve new traffic until the problems of congestion are greater than the benefit of additional traffic. *Practical Capacity* implies that there is a standard quality of the service that the railroad will maintain. *Economic Capacity* is determined by calculating the traffic level where the actual costs of congestion equals the revenues of additional traffic. The engineering capacity is the maximum flow through the network and often corresponds with high variability.

There are three broad categories to measure the level of service or capacity of a railroad as shown in Figure 1. The first is the throughput, the amount of goods and people that the transportation network serves per unit of time. The second is reliability of the service provided by the transportation network. Higher reliability often requires more physical resources. Lastly there is the overall utilization of the existing assets. Poor asset utilization can consume the available capacity of the railroad network. A capacity expansion project can be undertaken to increase throughput as well as increase reliability. Often, capacity projects can be postponed if more efficiency can be gained out of the current physical infrastructure and thus improving asset utilization.

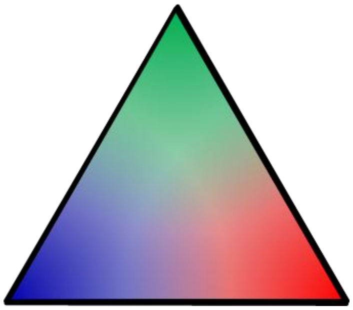

Figure 1: Capacity measurement interrelationships

Example railroad capacity metrics are summarized in Table 1. One of the most common metrics used for analysis is average train delay normalized by the length of route [4]. A high number for delay will indicate decreased reliability as well as poorer asset utilization. Longer delays will decrease the run time and subsequently decrease the cycle time. A major drawback of train delay as a metric is that it does not measure the throughput of the rail line. Another disadvantage is that train delay is more sensitive to train types with higher speeds. These faster trains can lose more time from their schedules when they are required to stop for other trains. Using train delay requires a baseline runtime to compare with the actual runtime. This baseline could be a minimum-run-time, (MRT), or a run time goal set by the service design group of the railroad.

Table 1: Classification of Railroad Performance Metrics

Amount Moved	Reliability	Asset Utilization
Trains	Distribution of Arrival Times	Dwell Time in Terminals
Cars	Average Train Delay	Blocking Time
Revenue Tons	Standard Deviation of Train Delay	Signal Wake
People	On Time Performance	Train Miles/Track Mile
TEUs	Crew Expirations	Idle locomotives
(per unit of time)	Average Velocity	Cycle Time

The highway capacity measurements are based on three key elements. The first is the average velocity of the vehicles through the highway network. Second is the density of the vehicles on the highway measured by the number of vehicles per mile. Lastly there is the flow of the highway measured by the number cars passing a given point per unit of time. Recently, highway analysis is adopting more variation analysis. Common highway measurements are summarized in Table 2 [5] and the formulations are in the appendix [5].

Table 2: Common Highway Metrics

Metric	Description
Velocity	The speed of which the vehicles travel through a network
Flow	The amount of vehicles passing a given point per unit of time
Density	The number of vehicles per unit length
Delay Per Traveler	The amount of additional time per person to reach a destination when compared to the free flow speed
Travel Time Index	The ratio of average trip time to free flow trip time
Planning Time Index	The ratio of the worst case likely scenario to the best case scenario
Buffer Time Index	The amount of slack time necessary in a passenger's schedule to have 95% on time performance
On Time Arrival Percentage	The percentage of vehicles arriving at their destination within a standard length of time
Volume to Capacity Ratio	The ratio of the current traffic levels to the maximum capacity of the highway
Misery Index	The ratio of the average of the slowest travel times 20^{th} percentile to the average travel time.
Level of Service	A qualitative grade (A-F) describing the capacity conditions of the highway as defined by the ASHTO Highway Capacity Manual

Velocity and flow are network barometers that are utilized by both highway and railroad industries. Velocity is measured as the average vehicle speed for both industries. Density is associated as a highway metric indicating the number of vehicles per mile for a given instant in time. The highway industry refers to flow as either hourly vehicle throughput or average daily traffic. The railroad commonly measure flow as trains per day or million gross tons per year.

The delay per traveler is analogous to the delay per train. The Travel Time Index is similar to a measurement of average delay. The Travel Time Index expresses the delay as a percentage of free flow time such that different roads can be compared regardless of their speed limits. Using the travel time index in delay analysis can mitigate the issue of delays having different consequences for trains with different speeds. The Planning Time Index and Buffer Time Index are metrics that measure the variation of travel times. The Planning Time Index measures the range of the travel time distribution by comparing the 95^{th} percentile of travel times to the free flow travel time. The Buffer Time Index determines the amount of additional time that should be added to the average trip time in order to have a 95% on time arrival percentage [5].

Consider a case where the free flow trip time is 20 minutes, the average trip time is 30 minutes, and the 95^{th} percentile of trip times is 50 minutes. In order to be on time 19 out of 20 trips, the vehicle must add 20 minutes of slack time to its schedule and depart 20 minutes early. The Planning Time Index is 2.5 and the Buffer Time Index is 67. The Planning Time Index indicates that a likely slow travel time is x2.5 greater than the free-flow speed. The Buffer Time Index indicates that 67% of the average trip time should be added as schedule slack to maintain a 95% on time arrival percentage.

Measuring on time arrival percentage is another method of analyzing the reliability of highway vehicles and trains. This reflects the percentage of arrival times that are within a standard length of time. This metric is easy to calculate and to understand by outside parties. However, the standard of what is on-time and what is late is set by the operating agency and this standard can be manipulated. Additionally, there may be practices where certain delays are not included in travel time.

The volume to capacity ratio measures the extent that fixed infrastructure is being utilized. When this value is closer to 1, the network is congested, and have limited ability to handle future traffic. This particular metric is not a measurement of traffic dynamics, but rather answers the question of where capacity constraints are prevalent in the network.

TRAFFIC RELATIONSHIPS

The Greenshield fundamental highway diagram, as seen in Figure 2, indicates that as more traffic enters the highway, the flow of vehicles through the highway increases until a critical density of vehicles. The maximum flow of vehicles through the highway occurs at this point [6]. This maximum flow is considered to be the capacity of the highway and would correspond to the level of *Engineering Capacity*. After this point, additional vehicles to the system will decrease the flow through the system. The downward slopping section of the diagram corresponds to congested stop & go travel. Ultimately, the jam condition is reached where all vehicles on the highway are stopped and there is zero flow of vehicles through the network. This value corresponds to the *Jam Capacity* [3]. The upward and downward trend of this model is consistent with other highway models. The actual transfer from increasing traffic flow to decreasing traffic flow is a more unpredictable process than suggested by the Greenshield model.

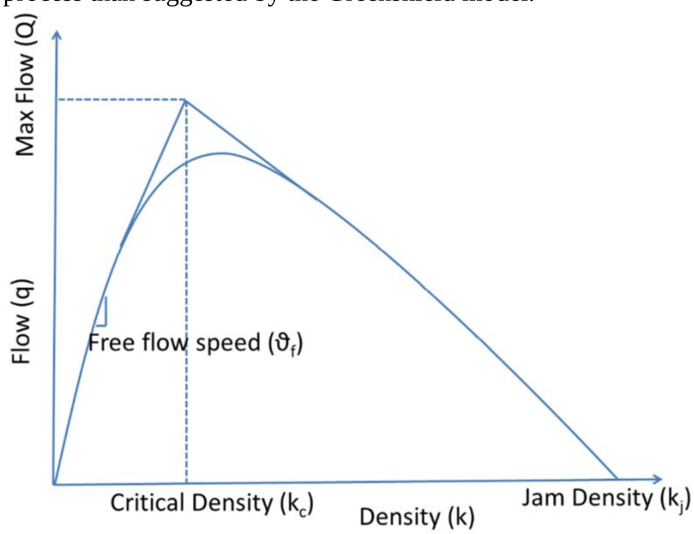

Figure 2: Greenshield fundamental traffic diagram indicating maximum flow

As shown in Figure 3, railroad transportation differs slightly from this highway diagram due to the unique operating characteristics. The shape of the curve represents the average train speeds. In single track the range of the speed distribution increases with traffic density due to the probability of being favored in a meet with another train. Under a single track scenario, there is large enough unreliability near the critical density that operating at this traffic level becomes impractical. In double track the speed distribution should remain narrow as trains do not need to stop as frequently. The train movements along a subdivision are controlled be a central dispatcher who can prevent additional trains entering the network after the critical density. Trains can be held in yards in order to preserve mainline flow. The railroad traffic control system also can prevent trains entering the mainline until there is a more favorable signal aspect or track warrant. However, these assumptions assume that the yards and terminals of the rail network are large enough to both hold trains from entering the mainline and provide the other terminal functions such as sorting, fueling, and inspections. If this assumption is relaxed such that terminals can become full, then the network flow will start to decrease with higher traffic densities similar to a highway network.

Another advantage that freight railroads have over both public transit and highways is that the demand of the infrastructure is usually uniform across a 24 hour period. Railroads can manage the demand and consequently build and maintain less infrastructure. The physical infrastructure is matched to this demand to improve asset utilization. Highways are designed to accommodate the high demand periods during the morning and evening rush hours. When a period of congestion does occur on a highway, the queue of traffic can overlap into a period of low demand and the highway can transition back into the free-flow condition. However, in a congested time period for a railroad, there is often not a time period of low demand to clear out congestion within the network. A severe derailment can back up railroad traffic for days as well cause lengthy detours.

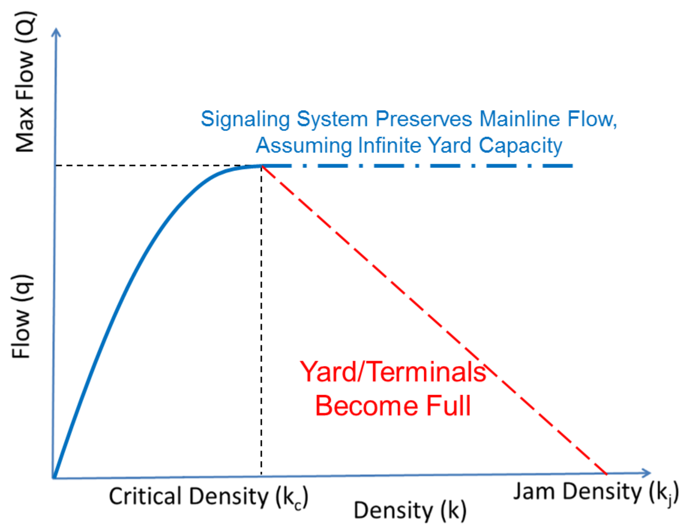

Figure 3: Applying the fundamental highway diagram to a railroad subdivision

A key relationship with railroad traffic is that higher traffic densities lead to higher delays as described in Figure 4. Each dot represents the delay of one bulk train. Without any improvements to the infrastructure, higher traffic levels correspond to higher delays with a broader range of run times. This curve would shift to the right if more track is added or if network efficiency were to increase. Each individual traffic mix has its own delay volume curve due to the additional delays from these trains interacting with each other.

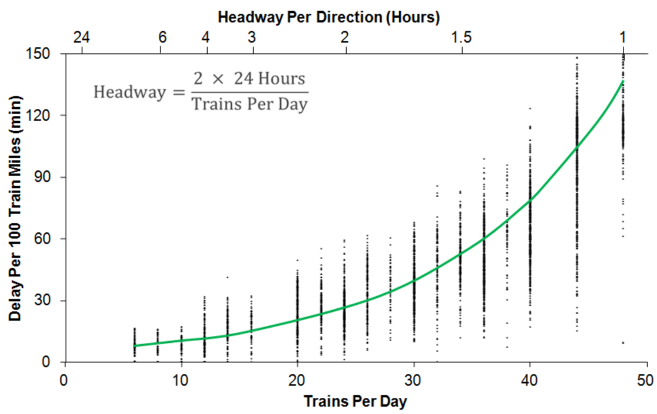

Figure 4: Delay volume relationship of railroad traffic

Unlike the highway fundamental diagrams, the delay volume curve does not clearly state what the capacity of the mainline should be. However, further analysis can allow the planning department of a railroad to devise a value of capacity from this curve. One method would be to state a maximum allowable average delay incurred by trains on the network. Figure 5 shows that if the standard (A) were set to 1 hour of delay per 100 train miles, than the capacity of the line would be 35 trains per day. A requirement based on the distribution of delays could also be utilized as well. The standard (B) could also be changed to the level of traffic where 15% of the trains are delayed 45 minutes or more per 100 train miles. This stricter standard would then state the capacity of same line would be 25 trains per day.

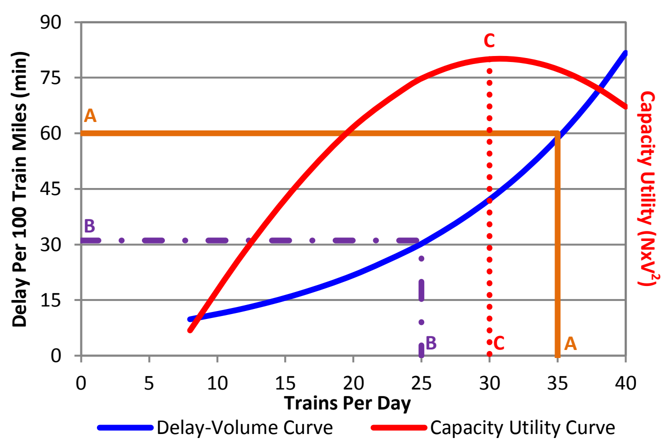

Figure 5: Finding the capacity form the delay volume curve

Another approach would be to utilize a utility model to estimate the capacity of the line. This utility model would incorporate the tradeoff between running more trains and decreasing the average velocity. This model would take the form as:

$$U = N^a V^b$$
$$U = \text{Capacity utility}$$
$$N = \text{Number of trains per day}$$
$$V = \text{Average train velocity}$$
$$a, b = \text{Exponents chosen by planner}$$

The capacity utility model would have a clear maximum value that will indicate the capacity of the line [7]. The maximum of the equation is dependent on the values that the planner chooses for a and b. The ratio between these two exponents would indicate the marginal rate of substitution between running more trains and decreasing average velocity. Using 1 for a and 2 for b would make the utility model analogous to the formula for kinetic energy $(1/2mv^2)$ where the number of trains is assumed to be the mass, m, and v is assumed to be average velocity of those trains. If these values are used for analysis of the line, then the capacity of the railroad line could be measured in physical units of energy. Using 1 for a and 2 for b, the capacity utility function is plotted in Figure 5. The maximum capacity of the line is at 30 trains per day, (C).

Transport Canada's second definition of Economic Capacity is illustrated in Figure 6. The capacity of the line is determined to be at the point where the marginal costs of additional traffic equal the marginal benefits of that traffic. The marginal cost curve is derived from costs both independent and dependent of congestion. There are fixed cost for running an additional train such as fuel, labor, locomotives, and rail cars that vary a small amount with increased traffic levels. At low traffic densities, these costs dominate the calculation of the marginal cost. At higher traffic levels, there is more delay as illustrated in Figure 4, and the cost of congestion dominates the marginal cost calculation.

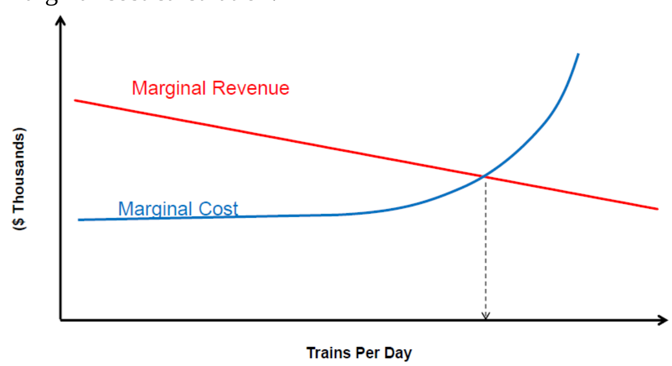

Figure 6: Economic analysis of railroad capacity

The marginal revenue curve can be assumed to be a horizontal when the price of a shipping cargo in railcar is assumed to be equal to the railroad's marginal revenue per railcar. This assumption indicates that the railroad industry is perfectly competitive. The other extreme is the monopoly condition where the railroad has the power set their own prices. Under the monopoly condition, the marginal revenue curve is downward sloping with a slope steeper than that of the market demand curve. This indicates that railroad has the ability to lower prices in order to attract new traffic [8]. In practice, the market condition of the railroad can be between monopoly and perfectly competitive competition depending on geographic conditions or the commodities in question. Overall, this type of economic analysis requires data from a variety of sources. The fixed costs and revenues per train type are simple calculations. However, the cost per delay hour and the degree of market power to set prices are much more complex calculations.

SIMULATION CASE STUDY

The subsequent simulation analysis will use the previous analytical techniques to consider a shared corridor between 110 mph passenger trains and 50 mph freight trains. The simulation was conducted in Rail Traffic Controller (RTC) [9]. Single track operation was chosen because of its prevalence in the network and because it is more sensitive to marginal increases in rail traffic than double track configurations. Single track represents a worst-case scenario because it becomes saturated with traffic more quickly. The simulated route characteristics are in Table 3. The route is simplified as much as possible to facilitate comparison of the effects of key variables regarding traffic composition. The representative passenger and freight trains are shown in Table 4 [10].

Table 3: Route Parameters Used In Simulation Model

Parameter	Value
Type	Single Track (1 O-D Pair)
Length	265 miles
Universal crossover spacing	15 miles
Siding length	7,920 feet
Traffic control system	2-Block, 3-Aspect ABS
Average signal spacing	2.0 miles

Table 4: Train Parameters for Simulation Model

Parameter	Unit Freight Train	Passenger Train
Locomotives	x3 SD70	x2 P42
No. of Cars	115 hopper cars	11 Articulated Talgo Cars
Length (ft.)	6,325	500
Weight (tons)	16,445	500
HP/TT	0.78	15.4
Max Speed (MPH)	50	110
	± 20 minutes departure time	32.4 miles between stops

The base case for all comparisons is the homogeneous condition when the composition of total traffic is 100% unit freight trains at 24 trains per day. The locations of meets and passes were not planned in advance and were calculated by RTC. At this traffic level, there are 12 eastbound and 12 westbound trains with a train departing each origination yard every two hours. Each simulation includes the performance of all the trains that operate within 72 hour period. Each particular traffic mix was repeated four times.

The results presented here are not intended to represent absolute predictive measurements for a particular set of conditions. Rather, they are meant to illustrate comparative effects under different conditions.

At 24 freight trains per day, the freight trains average 31.8 minutes of delay per 100 train miles. The distribution of the delays is shown in Figure 7 at 24 freight trains per day, (A). An on time arrival for a freight train is considered to be within 90 minutes of the MRT. These 24 freight trains have an on time arrival performance of 63%. These trains are delayed mostly by meets with trains travelling in the opposing direction. The probability of a train being favored in a meet is 50%. So some trains will be perform better than the median and some will perform worse. The distribution is only slightly skewed to the right.

Passenger trains were systematically added to the freight train base case starting with 2 additional passenger train starts per day up to 16 additional passenger train starts per day. Passenger trains were only added in pairs to maintain directional balance, and were scheduled to start during daytime hours between 7:30 am and 8:00 pm. The headways for all trains were held constant throughout the simulation. Adding 12 passenger trains to a base of 24 freight trains will change the headway from two hours to 90 minutes between train starts at each yard.

Adding passenger trains increases the delays to those freight trains. With 8 additional passenger trains, the average delay to the freight trains increases from 31.8 minutes to 47.8 minutes of delay per 100 train miles. The distribution of the delays is shown in Figure 7 at 32 total trains per day (B). The delay distribution of the freight trains is no longer systematical but skewed significantly to the right. The reliability of the freight trains has decreased and the risk of experiencing high delays has increased significantly. The distribution of freight delays becomes more skewed at higher traffic levels as indicated in Figure 7. The red line represents the median train delay, while the intensity of the black band represents how close data is to the median value in 10% increments. This type of area graph can show changes in distribution over different traffic levels. This type of graphic can only show the delay-volume trend and distribution with respect to only one delay-volume curve.

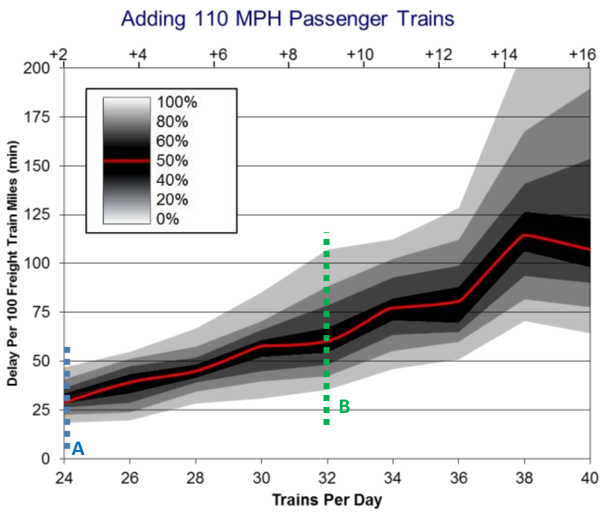

Figure 7: Distribution of freight delays at different numbers of passenger trains added to the network

For comparison purposes, a third scenario is explored. Instead of adding passenger trains to the base of 24 freight trains per day, the freight railroad adds more freight traffic to the line. This comparison serves to indicate that delays will increase regardless of train type when traffic levels increase.

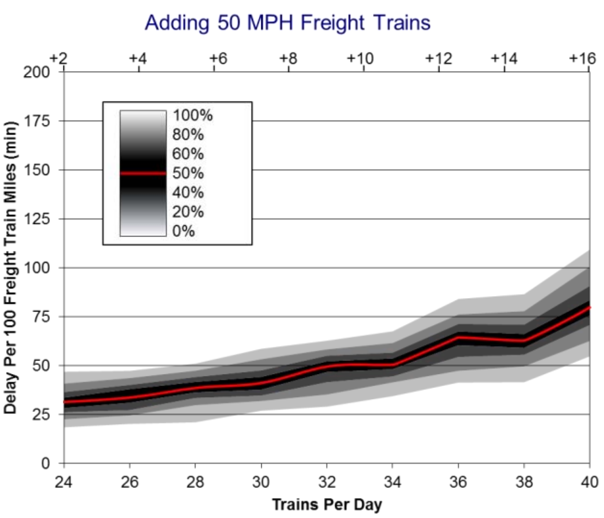

Figure 8: Adding more freight trains to base of 24 freight trains per day

As indicated in Figure 8, adding more freight trains per day increases the average train delay but not the skew of the distribution. The distribution of freight train delays remains symmetrical across all traffic levels. Without analyzing the freight only scenario, the negative impact to the freight trains would be linked solely to the passenger trains. The freight only analysis shows that freight delays would have increased with higher traffic levels regardless of train type.

Table 5 shows the impact to the initial 24 freight trains per day by adding freight trains or by adding passenger trains. The passenger trains cause additional impact beyond the impact of having a higher number of freight trains per day. The average velocity and on time performance metrics have the same negative impacts.

Table 5: The Impact of Adding Passenger Trains and with Adding Freight Trains

Metric	Additional Trains Per Day	Adding Freight	Adding Passenger	Change
Delay Per 100 Train Miles (min)	+0	31.8	-	
	+4	38.0	46.1	+8.1
	+8	47.8	66.5	+18.7
Average Velocity (MPH)	+0	35.7	-	
	+4	34.5	33.1	-1.4
	+8	32.7	30.1	-2.6
On Time Performance (90 minutes for freight) (30 minutes for passenger) (263 Mile Route)	+0	63.0%	-	
	+4	32.6%	19.5%	-13.1
	+8	18.8%	9.4%	-9.4

Table 6 uses the same data and summarizes it using highway metrics. The Travel Time Index is similar to measurement of train delay. This value increases both by adding freight trains and by adding passenger trains to the base case. Adding passenger trains more negatively affected this metric than adding freight trains. The Buffer Time Index and Misery Index give insight into the distribution of run times of the freight trains. In the freight only case, the Buffer Time Index and Misery Index do not vary significantly with the number of trains per day. This indicates that worse performing trains are decreasing the quality of service at a similar rate as the average train with respect to the number of trains per day. When 4 passenger trains are added, these metrics increase by 4% and then double with 8 additional passenger trains. An advantage of using the Buffer Time Index and Misery Index is that control for increased delays due to increases in traffic levels.

Table 6: Using Highway Metrics to Compare the Impact of Adding Higher Speed Passenger Trains to a Freight Network

Metric	Additional Trains Per Day	Adding Freight	Adding Passenger	Change
Travel Time Index	+0	1.29	-	-
	+4	1.33	1.40	+0.07
	+8	1.41	1.55	+0.14
Buffer Time Index $\frac{\text{95th Percentile of Run Time} - \text{Avg. Run Time}}{\text{Avg. Run Time}}$	+0	11.0%	-	-
	+4	11.1%	15.6%	+5%
	+8	10.8%	29.0%	+18%
Misery Index $\frac{\text{Avg. of Worst 20\% of all Travel Times}}{\text{Avg. Travel Time}}$	+0	9.5%	-	-
	+4	9.0%	12.8%	+3.8%
	+8	9.6%	23.5%	+13.9%

CONCLUSION

Capacity can be represented by increased throughput, reliability, and asset utilization. Capacity is a subjective measurement that can be analyzed using various techniques. Railroads share similar characteristics to the Highway fundamental traffic relationships but also have unique traffic relationships that differ from highway transportation. Highway analysis can help railroads analyze simulation data. Averages do not tell the whole story of the data and looking at the worse performing trains can give better insight to traffic dynamics. Additional higher speed passenger trains increases the delays to freight trains more so than an additional freight train. The worst performing freight trains are more sensitive to the higher speed passenger trains.

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APPENDEX

FORMULATION OF COMMON HIGHWAY METRICS

Velocity: Distance Covered for Unit Time

- Time Mean Speed: Total average speed of vehicles passing over a fixed point:

$$V_t = \left(\frac{1}{m}\right)\sum_{i=1}^{m} v_i$$

V = Average speed
m = Number of vehicles over a period of time
v_i = Instantaneous speed of vehicle i

- Space Mean Speed: Average speed of vehicles travelling over a segment of highway in one instant of time

$$V_s = n \Big/ \sum_{i=1}^{n} (1/v_i)$$

V = Average speed
n = Number of vehicles on a segment of roadway
v_i = Instantaneous speed of vehicle i

Density: Number of vehicles per unit length of the roadway.

$$K = \frac{n}{L}$$

K = Density of vehicles
n = Number of vehicles over a segment of roadway

Flow: The number of vehicles passing a reference point per unit of time

Delay Per Traveler: The amount of additional time per person to reach a destination when compared to the free flow speed

$$\mathrm{DPT} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} (T_{a_i} - T_{FF})/O$$

DPT = Delay per traveler
n = Number of vehicles on a segment of roadway
T_{a_i} = Actual travel time of vehicle i
T_{FF} = Free flow travel time
O = Average vehicle occupancy

Travel Time Index: The ratio of average tip time to free flow trip time

$$\mathrm{TTI} = \left(\frac{1}{nT_{FF}}\right)\sum_{i=1}^{n} T_{a_i}$$

TTI = Travel time index
n = Number of vehicles on a segment of roadway
T_{FF} = Free flow travel time
T_{a_i} = Actual travel time of vehicle i
O = Average vehicle occupancy

Planning Time Index: The ratio of the worst case likely scenario to the best case scenario

$$\text{PTI} = \frac{T_{95}}{T_{FF}}$$

$$\begin{aligned} \text{PTI} &= \text{Planning time index} \\ T_{95} &= 95^{\text{th}} \text{ percentile of travel times (slow trip times)} \\ T_{FF} &= \text{Free flow travel time} \end{aligned}$$

Buffer Time Index: The amount of slack time necessary in a passenger's schedule to have 95% on time performance

$$\text{BTI} = \frac{T_{95} - T_{AVG}}{T_{AVG}} \times 100\%$$

$$\begin{aligned} \text{BTI} &= \text{Buffer time index} \\ T_{95} &= 95^{\text{th}} \text{ percentile of travel times (slow trip times)} \\ T_{AVG} &= \text{Average travel time} \end{aligned}$$

On Time Arrival Percentage: The percentage of vehicles arriving at their destination within a standard length of time

$$\text{OTA} = \left(\frac{1}{n}\right) \times \left(\sum_{\{T_a : Ta \le T_S\}} 1\right) \times 100\%$$

$$\begin{aligned} \text{OTA} &= \text{On time arrival percentage} \\ T_a &= \text{Actual travel time} \\ T_S &= \text{On time standard (units of time)} \end{aligned}$$

Volume to Capacity Ratio: The ratio of the current traffic levels to the maximum capacity of the highway

$$\text{V/C} = \frac{q_{avg}}{q_{max}}$$

$$\begin{aligned} \text{V/C} &= \text{Volume to capacity ratio} \\ q_{avg} &= \text{Average vehicle flow in time period of analysis} \\ q_{max} &= \text{Maximum roadway throughput} \end{aligned}$$

Misery Index: The ratio of the average of the slowest travel times 20th percentile to the average travel time.

$$\text{MI} = \left(\frac{T_{20}}{T_{avg}} - 1\right) \times 100\%$$

$$\begin{aligned} \text{MI} &= \text{Misery index} \\ T_{20} &= \text{Mean of the slowest 20\% of all trip times} \\ T_{avg} &= \text{Average travel time} \end{aligned}$$

Level of Service: A qualitative grade (A-F) describing the capacity conditions of the highway as defined by the ASHTO Highway Capacity Manual

- **Level-of-Service A** describes free-flow operations. Traffic flows at or above the posted speed limit and all motorists have complete mobility between lanes.
- **Level-of-Service B** describes reasonable free-flow operations. Free-flow (LOS A) speeds are maintained, maneuverability within the traffic stream is slightly restricted.
- **Level-of-Service C** describes at or near free-flow operations. Ability to maneuver through lanes is noticeably restricted and lane changes require more driver awareness. Minor incidents may still have no effect but localized service will have noticeable effects and traffic delays will form behind the incident. This is the targeted LOS for some urban and most rural highways.

- **Level-of-Service D** describes decreasing flow levels. Speeds slightly decrease as the traffic volume slightly increases. Freedom to maneuver within the traffic stream is much more limited and driver comfort levels decrease.
- **Level-of-Service E** describes operations at capacity. Flow becomes irregular and speed varies rapidly because there are virtually no usable gaps to maneuver in the traffic stream and speeds rarely reach the posted limit. Any disruption to traffic flow, such as merging ramp traffic or lane changes, will create a shock wave affecting traffic upstream.
- **Level-of-Service F** describes a breakdown in vehicular flow. Flow is forced; every vehicle moves in lockstep with the vehicle in front of it, with frequent slowing required. Technically, a road in a constant traffic jam would be at LOS F.