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PARAMETRIC MODELING IN RAIL CAPACITY PLANNING

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ABSTRACT

This paper describes the development and application of a Parametric Model at Canadian National Railway (CN) for use in rail capacity planning. The Parametric Capacity Model is a practical tool used to help improve track asset utilization through the measurement and monitoring of system track capacity.

Understanding capacity is essential for determining the amount of traffic that can be moved over a rail system and degree of service & reliability that can be expected. The Parametric Capacity Model was developed to provide this understanding by measuring Theoretical, Practical, Used & Available track capacity.

1 INTRODUCTION

The effective management and utilization of assets becomes more important as Railways strive to reduce cost, improve service and handle increased traffic. The Parametric Capacity Model was developed as a tool to help manage railway track assets by measuring Theoretical, Practical, Used and Available track capacity.

Capacity has been a significant issue in the railway industry. Over the past 30 years numerous approaches and tools have been developed to address it. Common to all has been a focused analysis of only specific or localized problems for a given set of conditions. These approaches do not provide a broad assessment of capacity (i.e. corridor or system perspective) and to do so would be cost and time prohibitive due to the massive data and manpower requirements.

The Parametric Capacity Model is intended to fill the void between simple empirical formulae and detailed simulation models by focusing on the capacity relationship of key plant, traffic and operating factors. It provides a broad, system perspective of capacity by measuring the practical capacity of individual subdivisions of a rail network. The model provides a common measurement for all corridors and quickly highlights the capacity "bottlenecks" on the system.

The Parametric Capacity Model is also significant in that it incorporates cross-functional needs for capacity. It considers the competing demands by Engineering, Operations and Marketing for capacity to accommodate track maintenance, train service plans and traffic priorities respectively.

The Parametric Capacity Model is a decision support tool for the management of CN's largest asset, trackage. By measuring and monitoring track capacity the model will improve track asset utilization, increase service reliability and reduce capital costs.

2 OBJECTIVES

The objective of the Parametric Capacity Model is to be a practical tool to measure the capacity of individual subdivisions of a rail network, as illustrated in Figure 1;

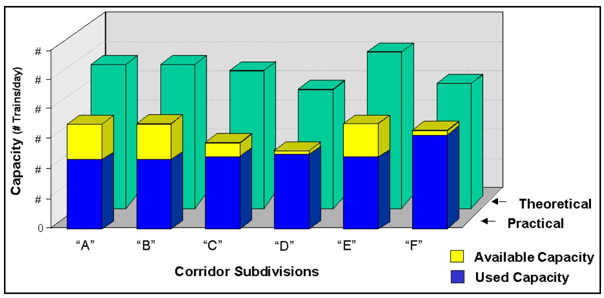


Figure 1: Corridor Capacity Measures

The Parametric Capacity Model makes comparisons of capacity for subdivisions in a corridor and identifies areas of either limited capacity (bottlenecks) which require remedial action or areas of over capacity that could be marketed for increased traffic.

To accomplish this, the parametric model;

- Recognizes the dynamic nature of capacity,

- Measures Theoretical, Practical, Used & Available Track Capacity,
- Facilitates cost/benefit tradeoffs, "what-if analysis"
- Requires minimal resources.

By focusing on how changes in key plant, traffic, and operating parameters affect track capacity, the model recognizes the dynamic, real-world nature of capacity. It highlights the fact that capacity is not static but varies with changes in track configuration, train schedules and service expectations.

Providing measures of different types of capacity allows insight into the competing demands and expectations for capacity by Marketing, Operations, and Engineering. Good information leads to improved decisions on how to increase capacity by balancing the different needs.

The Parametric Capacity Model will facilitate cost/benefit analysis by providing a quick means to simulate different plant, traffic or operating alternatives. "What-if" analysis can be performed with minimal resources to develop cost effective solutions to improve service reliability and handle more traffic.

The Parametric Capacity Model improves capacity management and leads to increased track asset utilization.

3 PRINCIPLES AND ASSUMPTIONS

The following sections describe the principles and assumptions used in development of the Parametric Capacity Model.

3.1 Defining Capacity

Capacity is a complex, loosely defined term that has numerous meanings. It is limited by the physical capabilities of the plant as well as affected by the traffic and operating conditions imposed on it. Capacity can be generally described as;

> *Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan.*

This could mean anything from the number of tons moved, speed of trains, on-time-performance, available track maintenance time, service reliability, or maximum number of trains per day that the subdivision can handle. Each are definitions/measures of capacity, but few are comparable or compatible to each other.

For example, increasing tons moved could mean longer heavier trains which are slower and lead to reduced train speeds for the line, while increased train speeds require shorter and lighter trains, but potentially less tons moved for the same crews and locomotives

In developing the Parametric Capacity Model, track capacity was defined as;

> *The highest volume (trains per day) that can be moved over a subdivision (plant) under a specified schedule and operating plan (traffic and operations) while not exceeding a defined threshold (over-the-road-time).*

This definition emphasizes the dynamic nature of capacity and identifies the fundamental factors that affect it. It recognizes that capacity is not static but varies with changes in plant, traffic or operating conditions as well as the expected level of service. It also states that capacity is to be measured in simple terms, as the number of trains per day relative to a specified threshold (over-the-road-time).

3.2 Measures of Capacity

The Parametric Capacity Model provides a measure for different types of capacity, which are illustrated in Figure 2.

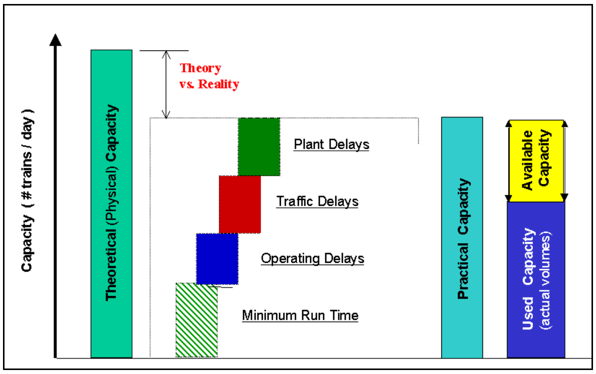


Figure 2: Types of Capacity Measures

The following describes the various measures of Theoretical, Practical, Used and Available Capacity;

Theoretical (Physical) Capacity: This is the theoretical maximum upper boundary of capacity. It assumes all trains are the same, with the same train consist, equal priority, and are evenly spaced throughout the day with no disruptions. It ignores the effects of variations in traffic and operations that occur in reality. Theoretical (Physical) Capacity is a function of the most restrictive plant segment i.e. the longest siding grid for single track or the max signal wake for double track. It is calculated using the following empirical formula (1);

$$N = \left(\frac{1440 \text{ min/day}}{E_t + W_t + V_t} \right) \times 2E_f \qquad (1)$$

Where:

N = Theoretical number of trains per day
E_t = Eastbound transit time
W_t = Westbound transit time
V_t = Acceleration & deceleration time
E_f = System efficiency (60, 70 and 80 percent for train order, ABS & CTC respectively)

Practical Capacity: The practical limit of "Representative" traffic volume that can be moved on a line while achieving a defined performance threshold. "Representative" traffic reflects actual train mix, priorities, consists, power to weight, and traffic bunching. The performance threshold is defined as the upper limit of acceptable over-the-road-time (ORT) for priority traffic, either from schedule or calculated as minimum run time plus 10% but limited to maximum train crew on duty time. It is currently determined by discrete event simulations of incremental traffic levels (which is time and resource demanding) or simply approximated as 2/3 (67%) of Theoretical Capacity.

Used Capacity: The actual traffic volume occurring over the territory. Reflects actual variation in traffic and operations that occur on the line.

Available Capacity: The difference between Used and Practical Capacity. It is an indication of the additional traffic volume that could be handled while maintaining the predefined performance threshold.

Practical Capacity is the most significant measure of track capacity since it relates the ability of a specific combination of plant, traffic and operations to move the most volume within an expected service level.

3.3 Parameters Affecting Capacity

3.3.1 Plant Parameters

Length of the Subdivision: The distance in miles between the beginning and end limits of the subdivision. Typical limits are from yard to yard or crew-change to crew-change point, and are roughly 125 miles for single subdivision. As the length of the subdivision increases typically so does the transit time of trains. This means more meets and overtakes, longer crew on duty time and more variability. These all limit capacity.

Meet Pass Planning Point Spacing (MPPPS): The average spacing of locations used to meet or overtake trains. Such locations are essential for the operations of bi-directional, mixed priority & speed trafficThe average spacing of Meet Pass Planning Points (MPPP) for a subdivision is calculated as (2);

$$\text{MPPPS} = \frac{\text{Length of Subdivision (miles)}}{(\text{Number of MPPP} + 1)} \qquad (2)$$

Locations with multiple sidings are considered to have only one. Sidings less than a standard train length, or ineffective for normal operation, are disregarded.

Meet Pass Planning Point Uniformity (MPPPU): This is the measure of uniformity or consistency in spacing of MPPP. Capacity increases as uniformity of plant, traffic or operations increase. It is a ratio of the standard deviation vs. average spacing and is calculated as follows (3);.

$$\text{MPPPU} = \frac{\text{Std Dev of MPPP Spacing}}{\text{MPPPS}} \qquad (3)$$

A uniformity value of zero represents a plant with equally distributed MPPPs

Intermediate Signal Spacing Ratio (ISSR): This is a parameter relating the ratio of signal spacing to the siding spacing. Intermediate signals increase capacity by reducing the required spacing between following trains, allowing trains to fleet. This is beneficial in moving larger traffic volumes, recovering from disruptions and reducing delays in overtakes and double meet situations. When calculating the ISSR each MPPP is assumed to have a signal. For territory with no intermediate signals the ISSR equals siding spacing. Is is calculated as (4);

$$\text{ISSR} = \frac{\left(\frac{\text{Length of Subdivision}}{(\text{MPPP} + 1 + \text{No. Signals})} \right)}{\text{MPPPS}} x100 \qquad (4)$$

Percent Double Track (% DT): Double or multiple track segments have a significant impact on a track's ability to move trains. Capacity of a line rises quickly with properly spaced sections of double track because it allows for running meets and more than one train in a segment. Signals and crossovers enhance this further. Percent Double Track is calculated as the ratio of double track vs. the length of the territory (5).

$$\%\,\text{DT} = \frac{\text{Miles of Double Track}}{\text{Length of Subdivision}} x100 \qquad (5)$$

Segments greater than 6000ft but less than 2 miles are considered as sidings. Generally, locations less than 6000 ft are ignored.

3.3.2 Traffic Parameters

Traffic Peaking Factor (TPF): A measure of concentration of traffic within a short time frame often called bunching or peaking. TPF has a significant impact on capacity because it can result in traffic levels higher than the territory could reliably sustain. When this occurs the effects are felt for a considerable time into the future as the system recovers from the overload.

The TPF evaluates the amount of traffic on the entire length of the subdivision at one time. It is designed to be non-directional and includes trains in both directions. TPF accounts for the interaction between opposing trains and the conflict involving with overtaking (passing) trains. It is calculated as the ratio between the maximum number of trains dispatched in a 4-hour period vs. the average number of trains for that time length (6).

$$\text{TPF} = \frac{\text{Maximum Trains in 4 hours}}{\text{Average Trains in 4 hours}} \qquad (6)$$

Priority Probability (PP): The priorities of trains play a vital role in deciding which trains will experience delay. Train priorities decrease capacity because priority trains are given preferential treatment over lower priority trains, which result in increased delays. Basically, priority generates a two-tiered dispatching procedure where low priority trains are delayed by each other plus must both clear well in advance and not use the plant needed by priority trains. This basically allows the priority traffic to move as if they alone were on the territory. As a rule, the greater the number of priority classes, the less capacity is available.

Priority is quantified using a probability function that identifies the chances of a train meeting another train of a higher priority. To simplify the approach only four train priorities are considered; Passenger, Express, Freight and Unit. Each train is assigned a priority associated with their speed class. The priority parameter is calculated as (7);

$$\text{PP} = \frac{1}{T} \sum_{i=2}^{N} \left(\frac{Ci}{(T-1)} \sum_{j=1}^{i-1} Cj \right) \qquad (7)$$

Where:

N = Number of priority classes (4 max)
T = Daily number of trains
Ci, Cj = Number of ith, jth priority class trains

Speed Ratio (SR): This parameter reflects the traffic mix operating over the subdivision in terms of speed capability. The speed differential between trains can significantly increase delay on a subdivision by generating overtakes and/or holding trains in yards to avoid conflicts/overtaking on line. The speed ratio is based on the following assumptions;

a) it is non-directional because train speeds affect both opposing and overtaking traffic,
b) the slowest and fastest trains are assumed to be on-line at the same time.

Speed Ratio is calculated as the ratio of fastest to the slowest train speed (8);

$$\text{SR} = \frac{\text{Fastest Train Speed}}{\text{Slowest Train Speed}} \qquad (8)$$

Average Minimum Run Time (AMRT): A significant parameter affecting capacity is average train speed. Higher speeds reduce both delay and transit time. This is because faster trains spend less time traveling a given distance, occupy the track for less time and move between MPPP's. Faster trains will spend less time waiting for conflicts to clear since opposing trains are faster as well.

Average speed is measured as the average minimum run time (MRT) of all trains in each direction, as obtained from a Train Performance Calculator (TPC). The TPC results incorporate the performance characteristics of the locomotives, resistance of the train consist, topography and speed limits of the territory traversed.

3.3.3 Operating Parameters

Track Outages (TO's): Track outages are planned and unplanned events that take a track out of service. This greatly affects the capacity of a line because it directly reduces the number of hours available in the day to move trains. Track outages usually occur due to maintenance, which is scheduled to minimize train impact, but can also be attributed to plant and train failures such as broken rail, signals, slides & washouts, accidents, equipment problems.

The effect of track outages is dependent on many factors; the number and duration of outages, location with respect to sidings, single and double track, and trains on-line or planned to move during the outage. Capacity is sensitive to the occurrences and duration that traffic cannot travel over the subdivision. The Track Outage parameter is defined below (9) as the number of hours the plant is out of service.

$$\text{TO's} = \frac{\text{Total Duration of Outages}}{\sum_{i=1}^{n} \frac{1}{n_T d_i}} \qquad (9)$$

Where:

n_T = total number of outages per day
d_i = duration of each outage (hrs)

Temporary Slow Orders (TSO's): Like track outages, TSO's have an impact on capacity. They are often maintenance related and can apply for a distance or at a single point on the line. TSO's generate two types of delays; 1) the time loss due to operating at slower than normal speed, 2) acceleration and deceleration time, called V time. The TSO parameter is calculated as follows (10, 11 & 12);

$$TSO's = Vtime + TravelTime \qquad (10)$$

$$Vtime = \frac{(V_m K - TSOSpeed)}{A} + \frac{(V_m K - TSOSpeed)}{D} \qquad (11)$$

$$TravelTime = \left(\frac{L}{TSOSpeed} + \frac{L}{(V_m \times K)} \right) \times 60 \qquad (12)$$

Where:

V_m = maximum freight speed (60mph)
K = % of time running at max speed (85%)
A = acceleration rate (20 mph/min)
D = deceleration rate (30mph/min)
L = length of TSO + average train length

Train Stop Time (TST): This parameter accounts for the amount of time trains spend stopped on line doing work. It is a delay that directly increases the amount of time a train takes to traverse subdivision. This time is expressed in hours and is additive to the Average Minimum Run Time.

Maximum Trip Time Threshold (MTTT): This parameter represents the upper limit of acceptable over-the-road-time (ORT) for priority trains. It is expressed in hours transit time and is the critical factor which, in combination with the other plant, traffic and operating parameters, is used to calculate the Practical Capacity of a subdivision.

4 CAPACITY EQUATIONS

The Parametric Capacity Model measures the capacity of subdivisions of a rail network by predicting the train delay vs. volume capacity curve (Figure 3) of a subdivision. It achieves this based on the relationships between the key parameters which affect the traffic handling capability of a subdivision.

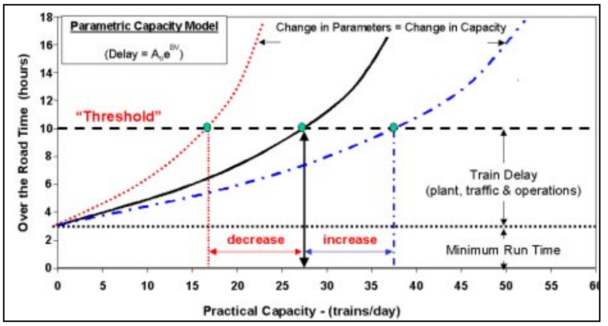


Figure 3: Track Capacity Curve

The relationship between train delay and traffic volume was found to be best expressed by the following exponential equation (13);

$$\text{Train Delay} = A_o e^{BV} \qquad (13)$$

Where:

A_o=Parametric Plant, Traffic, Operating Coefficient
B = Constant
V = Traffic Volume

The relationship between train delay and the parametric values are expressed by the coefficient "A_o". This value is unique for each specific combination of parameters defined by the Plant, Traffic and Operating conditions of a subdivision. As these parameters change, so do "A_o", resulting in a new capacity curve. A different value of "A_o" will define a new capacity curve which in turn defines a new Practical Capacity for the specified threshold.

Capacity relationships were developed through use of event based simulation models. The results of the simulations describe how the key plant, traffic and operating parameters define the capacity curve of a subdivision.

Focusing on each parameter individually numerous simulations were done with incremental traffic volumes and parameter values. All other parameters were held at their base values. This defined a capacity curve and identified one "A_o" value.

The value for parameter was incremented and simulations were redone to define other capacity curves and "A_o" value. Following this process various capacity curves, and subsequently "A_o" values, were identified for a range of values for each parameter, as illustrated by Figure 4.

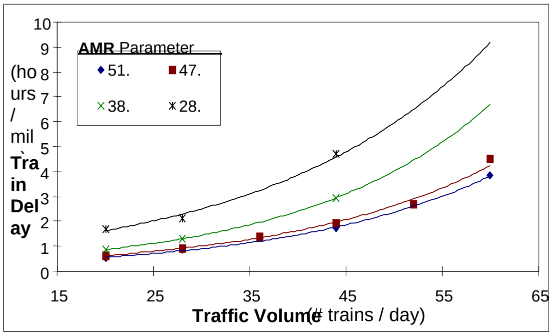


Figure 4: Capacity Curves for Different AMRT

For each parameter, an equation was developed describing the relationship between "A_o" and changes in parameter values, example below (Figure 5);

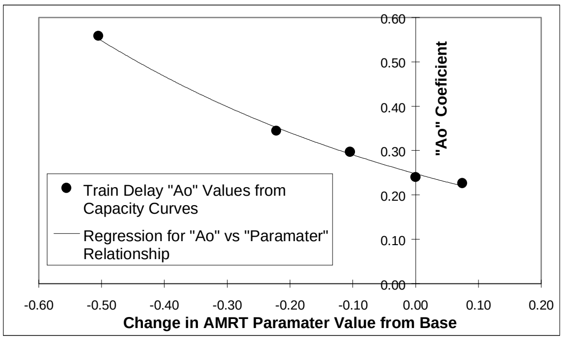


Figure 5: AMRT "Ao" vs. Parameter Relationship

It is through these relationships that the Parametric Capacity Model is able to provide a measure of Practical Capacity for a subdivision to move traffic under specific conditions and within specified thresholds.

Comparisons were made between the results provided from the Parametric Capacity Model to that from detailed discrete event simulations to check the validity of the Parametric Capacity Model (Table 1).

Table 1: Parametric vs. Simulation Results

		Simulation	Parametric			
Subdivision	No. Trains	Avg. Delay (hours)	Avg. Delay (hours)	Dif	%error	Absolute Error
Skeena	19	0.69	0.81	0.12	17%	17%
Telkwa	14	0.67	0.74	0.07	10%	10%
Nechako	22	1.01	1.18	0.17	17%	17%
Fraser	14	1.12	1.12	0.00	0%	0%
Ruel W.	19	0.59	0.53	-0.06	-10%	10%
Bala N.	17	0.82	0.78	-0.04	-5%	5%
Ruel E.	19	0.86	0.82	-0.04	-5%	5%
Watrous W.	28	0.96	0.96	0.00	0%	0%
Wainwright E.	26	0.8	0.79	-0.01	-1%	1%
Allanwater	17	0.55	0.47	-0.08	-15%	15%
Napadogan	19	0.85	1.11	0.26	31%	31%
Average		0.81	0.85	0.04	4%	10%

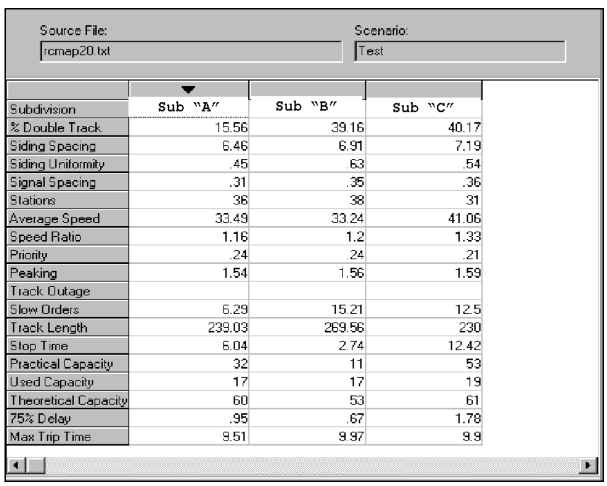
The results show that the Parametric Capacity Model was on average within 10 percent of that from detailed line simulation, with the exception of the Napadogan Subdivision. The higher parametric delay for the Napadogan subdivision is attributable to omitting a number of short sidings in the calculations for the plant parameters. This changed the MPPPS and MPPPU parameters to less favorable values resulting in lower capacity and higher train delay.

This demonstrates the importance in ensuring quality information in determining the parameters. It also highlights the importance in ensuring the parameters reflect the real world. The results in table 1 confirm that the Parametric Capacity Model can provide meaningful capacity measures.

5 PARAMETRIC CAPACITY MODEL

The Parametric Capacity Model is a capacity tool which falls between the empirical Theoretical Capacity formula and detailed line simulation models. It is a Windows 95 based program which models the capacity of a railroad by predicting the stress-strain capacity curve of a subdivision through parametric relationships for key Plant, Traffic & Operating parameters. It is quick and easy to use and provides capacity measures for any number of subdivisions at a time, enabling it to assess a corridor or network at once.

The only data required to run the model are values for the plant, traffic and operation parameters. This data can be input manually or through an import procedure which takes an ASCII file description of the plant (stations & mileage), train schedules (class, time, origin & destination), stop times, track outages and slow orders to calculate all the parameters at once (Figure 6).


Source File: rcmap20.txt
Scenario: Test

Subdivision	Sub "A"	Sub "B"	Sub "C"
% Double Track	15.56	39.16	40.17
Siding Spacing	6.46	6.91	7.19
Siding Uniformity	.45	.63	.54
Signal Spacing	.31	.35	.36
Stations	36	38	31
Average Speed	33.49	33.24	41.06
Speed Ratio	1.16	1.2	1.33
Priority	.24	.24	.21
Peaking	1.54	1.56	1.59
Track Outage			
Slow Orders	6.29	15.21	12.5
Track Length	239.03	269.56	230
Stop Time	6.04	2.74	12.42
Practical Capacity	32	11	53
Used Capacity	17	17	19
Theoretical Capacity	60	53	61
75% Delay	.95	.67	1.78
Max Trip Time	9.51	9.97	9.9

Figure 6: Parametric Capacity Model Input

The outputs of the model are measures of Theoretical, Practical, Used and Available Capacity for each subdivision (Figure 7), based on the parametric input parameters.

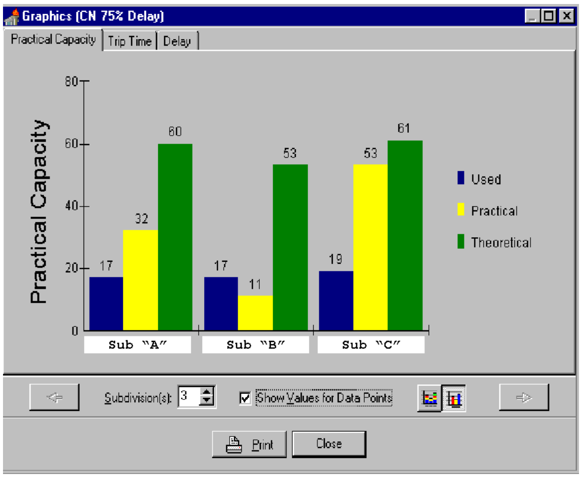


Figure 7: Parametric Capacity Model Output

The Parametric Capacity Model calculates Theoretical Capacity using the empirical capacity formula (1) from the plant and minimum-run-time data supplied during the ASCII data import procedure. Values of Used Capacity are supplied externally, either by the user import or fed from the Capacity Monitoring System, another system developed by CN to support capacity management. Available Capacity is the difference between the Used and Practical Capacity of each subdivision.

Alternatives can be quickly developed and assessed through the "What-if" component of model. This allows the user to change up to 3 parameters through a range of values and see the results graphically (Figure 8).

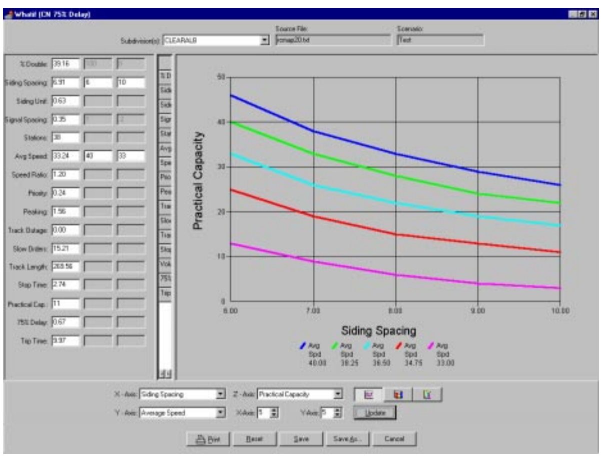


Figure 8: Parametric "What-If" Model

6 CONCLUSIONS

The Parametric Capacity Model is an effective decision support tool for capacity management. It recognizes the dynamic nature of capacity and provides a system wide capacity measure of subdivisions in a rail network. This allows comparisons of capacity to be made to identify area of limited (bottlenecks) or excess capacity.

The model will be used in Network Capacity planning to monitor system track capacity and support short and long term planning. This information will be used to develop cost effective solutions ranging from schedule to plant improvements. It will have input into train service design and Marketing decisions, improve service reliability and better meet customer requirements.

AUTHOR BIOGRAPHY

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