



Building capacity through structured heavy haul operations on single-track shared corridors in North America

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ABSTRACT: North American freight rail traffic reached a peak in 2006 on the strength of heavy haul transportation of bulk commodities and double-stack intermodal containers in international trade. However, the composition and geographic distribution of this traffic has substantially changed. Coal traffic has declined by over 20 percent since 2006 while intermodal traffic has reached record levels, with particularly strong growth in domestic intermodal traffic requiring predictable service on precise schedules. On the predominantly single-track North American rail network, allowing for schedule flexibility results in continually changing train meet and pass requirements that can increase train delay and constrain capacity, but also decrease utilization of capital-intensive infrastructure. This research uses simulation to investigate the relationship among line capacity, level of schedule flexibility, allowable train delay and the mixture of scheduled and flexible trains operating on a corridor. Rail Traffic Controller software is used to simulate different combinations of these factors. Based on the results of these simulations, practitioners can consider introducing more structured schedules for heavy haul traffic as one potential approach to building the capacity required to accommodate rising intermodal traffic on emerging shared corridors.

1 INTRODUCTION

Heavy haul railway operations provide for the safe, efficient, economical and reliable transportation of freight and bulk commodities in particular. A key to the efficiency of heavy haul operations is maximizing the amount of freight hauled by each train and continuously cycling rolling stock between loading and unloading points. To achieve these objectives, the departure and arrival times of heavy haul freight trains may be dictated by production timelines and vessel sailing schedules instead of a pre-planned railway timetable. Many heavy haul operations exhibit schedule flexibility with trains departing terminals at different times each day. Without a fixed timetable and pre-planned locations for each train meet on single track, flexible operations require train dispatchers to resolve train conflicts in real time. As this paper will demonstrate, for a given track infrastructure layout, these flexible operations consume more capacity than structured operations where trains depart within shorter time windows.

In North America, many corridors that were once dominated by heavy haul operations on flexible schedules are seeing increased numbers of intermodal trains that require more structured operations to meet business objectives. Although freight traffic volume in the United States peaked in 2006, follow-

ing three years of traffic declines due to economic recession, US freight rail traffic has slowly returned to 2006 levels. However, the composition and geographic distribution of this traffic has substantially changed. Coal traffic has declined by over 20 percent since 2006 while intermodal traffic has reached record levels, with particularly strong growth in domestic intermodal traffic requiring predictable service on precise schedules (AAR, 2016).

Heavy haul and intermodal trains have different train speed, priority, length, weight and level-of-service requirements. Maintaining the efficiency of heavy haul trains through schedule flexibility while simultaneously providing the consistent and reliable level of service required by intermodal trains presents a substantial operational challenge.

While infrastructure expansion may provide the required capacity for these two operations on a shared single-track corridor, it may be possible to maximize the capacity and level of service of these corridors by striking a balance between flexible and structured operation of heavy haul traffic.

This research investigates the relationship among line capacity, level of schedule flexibility, allowable train delay and the mixture of scheduled and flexible trains operating on a corridor. Simulation experiments are used to determine the capacity of a representative North American single-track rail corridor



as it transitions from purely flexible operation with random train departures to a highly-structured operation on a precise timetable designed to minimize train delay. The results of this study can be used to develop a better understanding of the interaction between line capacity and schedule flexibility. Ultimately this knowledge can help railway practitioners make trade-off decisions involving capacity and the level of flexibility allowed in their heavy haul operating plans.

2 BACKGROUND

2.1 *Structured and flexible operations*

As described in the introduction, most North American freight trains do not operate according to a prescribed timetable. Although the same general pattern of trains may be operated on a given day of the week from week-to-week, a specific train may depart a terminal over a range of times. Heavy haul freight trains that cycle between loading and unloading terminals may almost enter the network at random according to production and shipping schedules of bulk commodities. This type of operation is referred to as “improvised” or “flexible operation” (Martland 2010).

Flexible operations are in contrast to “structured operations” where a pre-planned timetable specifies exact departure times, locations of meets and passes with other trains, and arrival times at the destination terminal and intermediate points along the route (Martland 2010). Structured operation is common on rail networks in Europe and Asia and even some transit and commuter railways in North America.

In this paper, the term “schedule flexibility” is used to describe the amount of variation in departure times relative to a baseline train operating plan with target departure times. Operations with low schedule flexibility are more structured and will have all trains departing relatively close to their planned departure times. A completely structured operation will exhibit no schedule flexibility and all trains will depart at their precise scheduled time. Operations with high schedule flexibility will have train departures distributed over a wider range around the planned departure time. A completely flexible operation will have trains departing randomly during each day of operation.

2.2 *Previous research*

In the context of North American heavy haul operations, railway line capacity is defined by the largest traffic volume that can be operated on a route segment while maintaining a minimum level-of-service standard (Krueger 1999). The level-of-service standard corresponds to a maximum allowable average train delay. Train delay is calculated as the difference between the actual running time of a train over

a route segment and its minimum running time without interference from meets or passes with other trains. Capacity can be defined by the average train delay for all trains or may also consider level-of-service requirements that are specific to certain types of trains (Shih et al. 2015).

The Canadian National Parametric Capacity Model (Krueger 1999) describes relationships between train delay, traffic volume and various parameters describing track infrastructure, traffic and operating conditions. However, the model parameters do not explicitly consider the amount of schedule flexibility.

Martland (2003) modelled the link between heavy haul line capacity and terminal operations. Martland observed that capacity plans must account for disruptions and variability in operations. Martland also suggested that there may be ways to increase capacity through changes to operations that do not require infrastructure expansion. This view is shared by Ede and et al. (2007) who considered how to reach the most cost-effective heavy haul operation by balancing parameters involving infrastructure investment, train characteristics, operations and maintenance scheduling. It was suggested that variability in train departures throughout the day reduces capacity compared to an operation with evenly-spaced departures. Ede et al. (2007) also indicated that sharing the track with other types of trains presented a challenge for heavy haul operations capacity. Neither Martland or Ede et al. quantified their qualitative observations of the capacity effects of departure variability and interaction between types of trains.

Research on the capacity of a single-track corridor with heterogeneous train operations was conducted by Dingler who examined the interaction of higher-speed intermodal trains with lower-speed heavy haul bulk unit trains (Dingler 2010). The train delay response was highest on the simulated corridor when equal numbers of intermodal and unit trains were present on the corridor. However, the research did not consider different departure time flexibility for the two types of trains. Subsequent research confirmed that train delay increases as heterogeneity increases for randomized train departures (Sogin et al. 2013; Sogin et al. 2016).

Boysen (2012) built a capacity model that examined ways network capacity can be influenced by stakeholder needs, train characteristics and operating parameters. This model suggested that capacity could be increased by decreasing heterogeneity in the system but did not address schedule flexibility. Subsequent analysis of a heavy haul iron ore line in Sweden and Norway documented the heavy haul capacity consumed by dedicating timetable slots to passenger trains and maintenance activities (Boysen 2013). To operate passenger trains on a fixed timetable, the heavy haul iron ore trains must adhere to pre-planned timetable slots. To account for the flex-

ible departure of the iron ore trains according to production and shipment demand, the freight operator purchases more schedule slots than are needed to operate the average daily traffic volume (Lindfeldt 2010). Trains are held at terminals until their scheduled departure time and many slots go unused during times of low iron ore demand.

A case study of a Dutch railway line analysed the capacity of scheduled and flexible operations using two different train control systems (Goverde et al. 2013). The standard UIC compression method of capacity analysis was used to model scheduled trains but flexible trains required Monte Carlo simulation and rescheduling algorithms. The research focused more on the ability of each control system to handle unscheduled operations and less on the specific capacity effects of varying amounts of flexible operations.

Dick & Mussanov (2016) directly investigated the effect of varying amounts of schedule flexibility on train delay for fixed volumes of homogeneous rail traffic on representative North American single-track and partial-double-track lines. When starting from a fixed timetable with little train delay, introducing schedule flexibility in the form of random variation about the schedule departure time caused an increase in average train delay. Small amounts of schedule flexibility created rapid increases in train delay but beyond a certain level of schedule flexibility, further increases in train delay were not observed. Additional work investigated the relative delay performance of different combinations of scheduled and flexible trains operating on the same corridor across a range of schedule flexibility (Mussanov et al. 2017). The results suggest it is difficult for scheduled trains to have a high level of service in the presence of flexible trains and the effect is magnified as the line nears capacity.

2.3 Research hypotheses

This paper examines the relationships between schedule flexibility, train-type specific levels of service (allowable train delay) and the capacity of representative North American single-track corridors under combinations of flexible and scheduled freight trains.

Past study by Dick & Mussanov (2016) emphasized that for a given volume of trains operating with schedule flexibility, the incremental train delay response became increasingly insensitive to additional schedule flexibility (Figure 1a). It is also accepted that North American freight train delays increase exponentially with increasing train volume (Figure 1b) (Krueger 1999 and Dingler 2010). The shape of the relationship between delay and schedule flexibility for a constant volume in Figure 1a leads to the hypothesized family of delay-volume curves in Figure 1b. At high levels of schedule flexibility, the delay-volume curves in Figure 1b are more closely

spaced to correspond to the decreasing sensitivity of delay to schedule flexibility illustrated in Figure 1a. The simulation experiments described in this paper investigate if this hypothetical relationship can be observed on representative single-track corridors.

Figure 1b suggests a hypothesis that a higher traffic volume with lower schedule flexibility may exhibit the same average train delay as a scenario with a lower traffic volume, but a greater schedule flexibility. By setting a maximum allowable delay to serve as the level of service that defines line capacity, the corresponding combinations of volume and schedule flexibility yield a hypothetical relationship between schedule flexibility and capacity (Figure 1c). As schedule flexibility increases, line capacity is expected to decrease. The decrease in capacity from pure structure operation (zero schedule flexibility) represents the capacity penalty for allowing some trains to operate on flexible schedules. Similarly, moving from flexible schedules to more structured operations is expected to increase line capacity.

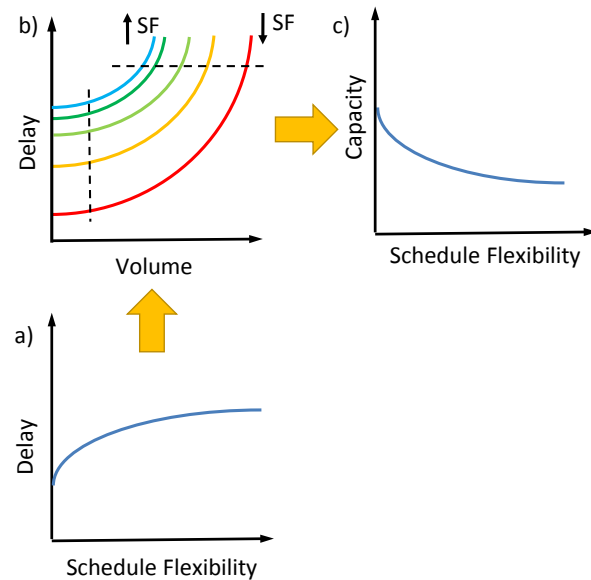


Figure 1. Combination of (a) Previously established relationship between schedule flexibility and train delay and (b) shape of the train delay-volume curve can be used to create a (c) hypothetical relationship between schedule flexibility and line capacity

3 METHODOLOGY

3.1 Rail Traffic Controller

This research develops train delay and capacity metrics with the use of Rail Traffic Controller (RTC), the industry-leading rail traffic simulation software in the United States. RTC is used by a wide range of public and private organizations, including most

Class I railroads, Amtrak, and rail operations consultants. Specially developed for the flexible North American railway operating environment, RTC emulates dispatcher decisions in resolving train meet and pass conflicts while simulating the movement of trains over rail lines subject to specific route characteristics. RTC allows users to alter different infrastructure, train and control system parameters in the simulation and analyse the train delay response.

RTC can dispatch trains according to a timetable for structured operations and also randomly for flexible operations. RTC dispatches scheduled trains from originating terminals at the specified time. Flexible trains depart terminals within a user-specified range before and after the planned departure time. For example, if the user assigns a schedule flexibility of 60 minutes to one train, RTC will randomly dispatch that train as early as 60 minutes before the planned departure or 60 minutes after the planned departure time. Within the interval of +/- 60 minutes, the departure time will vary for each simulated day according to a uniform distribution. RTC allows the user to specify a different amount of schedule flexibility for each train to be dispatched in the simulation. With this capability, RTC can simulate a representative route segment of the North American freight network carrying both heavy haul bulk commodity trains with schedule flexibility and high-priority intermodal trains with scheduled departure times.

The main output of the RTC simulation of interest to this research is the train delay response. Train delay is averaged by train type across all simulation days and normalized by the total train-miles (or train-km).

Since this research incorporates schedule flexibility, the exact train departure schedule is different for each simulated day and replication is required to achieve a stable average train delay response. To estimate the required number of replicates, one scenario in the experiment design was replicated 100 times with different initial random seeds for each five-day simulation. After seven replications, the average train delay stabilized. For this research, each scenario in the experiment design is replicated ten times with each simulation considering five days of train operations. For each scenario in the experiment design, this simulation plan yields train delay data for 50 days of train operations that are then averaged into a single train delay data point for those experimental conditions.

3.2 Baseline schedule

Trial-and-error was used to develop a combination of baseline schedule and infrastructure that minimized train delay for a traffic volume of 36 trains per day on a single-track corridor (Table 1). The baseline schedule follows the “return-grid” operating model where trains alternately depart from each end

terminal on even intervals and all train meets are designed to occur at evenly-spaced passing sidings. As described in the next section, this baseline schedule is perturbed through the introduction of schedule flexibility and changes in traffic volume to generate a range of experimental conditions. The route is 386 km in length with 23 passing sidings (passing loops) that are 3.22 km long and placed every 16 km on-center. All trains have the same 125-railcar consist and are representative of North American freight operations.

Table 1. Baseline schedule, route and train parameters

Parameter	Values
Length of route	386 km
Siding length	3.22 km
Siding spacing	16 km
Number of sidings	23
Traffic volume	36
Scheduled departure interval	2 hours
Maximum speed	37 km/hr
Locomotive type	SD70 3206 kW, 3 locomotives per train
Train consist	115 railcars at 125 tons each. 2.07 km total length
Operating protocol	CTC 2-block, 3-aspect

3.3 Experiment Design

Three variable factors were used to generate the different simulation scenarios in the experiment design: traffic volume, schedule flexibility and traffic composition (Table 2). While the route infrastructure was held constant, the baseline pattern of train operations was altered according to obtain the factor levels in Table 2.

Table 2. Experiment design factors and factor levels

Factor	Factor levels
Traffic volume	24, 28, 32, 36, 40, 44 trains per day
Schedule flexibility	+/- 0, 10, 60, 120, 720 minutes
Traffic composition (Percent of trains with flexible schedules)	0%, 25%, 50%, 75%, 100%

To vary the traffic volume, trains were added or removed from the initial baseline schedule of 36 train departures (Table 3). Trains were removed and added in pairs to maintain directional balance. Removing four trains from the ideal schedule for 36 trains provides the initial departure times for the scenarios with 32 trains per day. The remaining trains are not re-spaced to even intervals but remain in their original departure slots to preserve the ideal “return-grid” schedule. To increase traffic volume from 36 to 38 trains per day, four trains were dispatched in a time slot used for two trains in the baseline schedule. For 44 trains per day, the extra trains required doubling traffic in four of the original slots (Table 3).

The traffic volume on the line is comprised of two types of trains: scheduled and flexible. Scheduled trains follow the exact departure times specified in the baseline schedule regardless of the schedule flexibility factor level. Flexible trains randomly depart each terminal over the range of departure times relative to the baseline schedule specified by the schedule flexibility factor. As described in the previous section, ten minutes of schedule flexibility allows the flexible trains to depart any time within a 20-minute window extending ten minutes before the scheduled departure and ten minutes after. This research considers five levels of schedule flexibility: 0, 10, 60, 120 and 720 minutes. Zero schedule flexibility corresponds to a structured operation on the baseline schedule while 720 minutes corresponds to completely random departures over the entire day. Since the previous work of Dick & Mussanov (2016) found little incremental change in train delay for high levels of schedule flexibility, additional levels of schedule flexibility between 120 and 720 minutes were not simulated.

Table 3. Comparison of train slots for 32, 36, & 44 trains when the traffic compositions of 50% and 75%

Scheduled time (% flexible trains)	32 trains (50%)	36 trains (50%)	36 trains (75%)	44 trains (75%)
0:00:00	---	SS	SS	SS
1:20:00	FF	FF	FF	FF
2:40:00	SS	SS	FF	FF
4:00:00	FF	FF	FF	FFSS
5:20:00	SS	SS	FF	FF
6:40:00	FF	FF	FF	FF
8:00:00	SS	SS	SS	FF
9:20:00	FF	FF	FF	FFSS
10:40:00	SS	SS	SF	FF
12:00:00	---	FF	FF	FF
13:20:00	SS	SS	SS	FF
14:40:00	FF	FF	FF	FFSS
16:00:00	SS	SS	FF	FF
17:20:00	FF	FF	FF	FF
18:40:00	SS	SS	FF	FF
20:00:00	FF	FF	FF	FFSS
21:20:00	SS	SS	SS	SF
22:40:00	FF	FF	FF	FF

To determine if the relationship between schedule flexibility and capacity depends on the combination of scheduled and flexible trains on the route, different traffic compositions were included in the experiment design. This study considered traffic compositions where 0%, 25%, 50%, 75% and 100% of the trains operate with flexible schedules. For example, the scenario with a volume of 40 trains per day and 25% flexible trains will include 10 flexible trains operating with schedule flexibility and 30 scheduled trains following scheduled departures. Within the RTC simulation, higher priority is assigned to scheduled trains.

The combination of factors in the experiment design yields 150 different scenarios for simulation with RTC.

4 RESULTS

4.1 Capacity versus Schedule Flexibility

Train delays for the simulation scenarios in the experiment design were extracted to study the relationship between volume, schedule flexibility and traffic composition. To estimate line capacity, normalized average train delay values were plotted for each combination of traffic volume and schedule flexibility under a given traffic composition (Figure 2a). By setting a maximum allowable average train delay (minimum level of service for all trains) of 40 minutes per 160 train-kilometres, it is possible to estimate the line capacity as the maximum volume that can be supported at that level of service. In this manner, the trend lines in Figure 2a are used to construct a relationship between line capacity and schedule flexibility for a given traffic composition (Figure 2b).

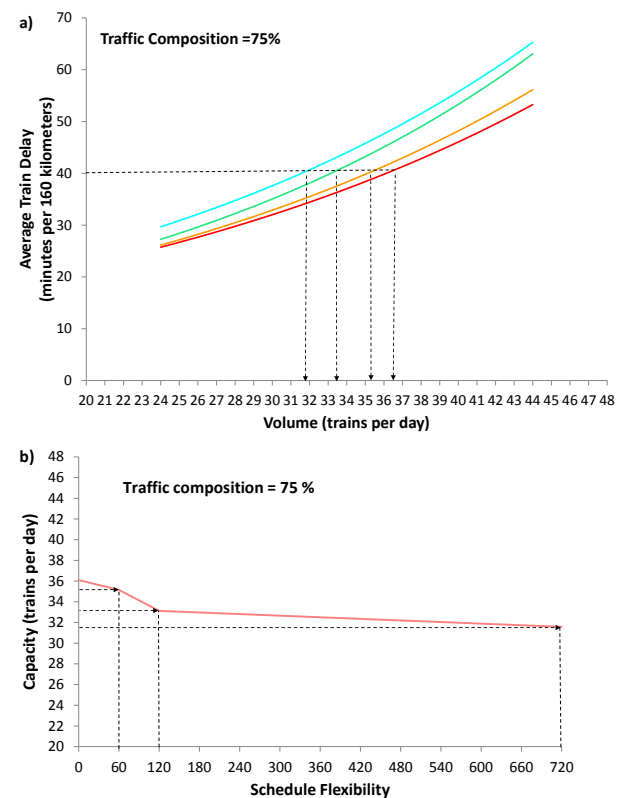


Figure 2. Example of capacity evaluation process a) Relationship between the average delay and train volume for different levels of schedule flexibility b) Capacity for a given schedule flexibility as defined by a maximum allowable train delay

The general appearance of Figures 2a and 2b follow the hypothesized relationships presented earlier (Figures 1b and 1c). For the specific case in Figure 2b, line capacity increases by approximately four trains per day when the flexible trains operating on the line transition from purely flexible to structured operations. This estimate of capacity only considers average train delay and not any train-type specific level-of-service requirements.

4.2 Regression analysis of train-type performance

To provide a comprehensive model of line capacity on the route under study, the general approach of Shih et al. (2015) was followed. A regression model with volume, traffic composition, and schedule flexibility as inputs and train delay specific to scheduled and flexible trains as an output was constructed (Equation 1). The model has an R-squared of 0.94 and significant interactions with p-values below 0.01. Thus the model should be a good predictor of the train delay associated with each type of train for the range of simulated factor levels.

$$D_t = f_t(c, SF) * V^2 + g_t(c, SF) * V + h_t(c, SF) \quad (1)$$

where c = traffic composition; SF = schedule flexibility; V = volume; g_t , f_t , h_t are functions representing first and second order functions of delay-volume function of a train type t ; and D_t is the average normalized train delay for train type t .

To create an expression for line capacity, Equation 1 is set to equal a maximum allowable delay for each train type and then solved for the corresponding traffic volume using the quadratic formula (Equation 2). This volume corresponds to the capacity of the line as defined by the level of service required for a particular type of train.

$$V^* = \frac{-g_t(c, SF) + \sqrt{g_t^2(c, SF) - 4 * f_t(c, SF) * (h_t(c, SF) - D_t)}}{2 * f_t(c, SF)} \quad (2)$$

where D_t^* is the maximum allowable average normalized train delay for train type t ; and V^* is the line capacity as defined by the level of service of train type t .

Using Equation 2 and given train-type specific level-of-service requirements of 21 minutes of delay per 160 train-km for scheduled trains and 38 minutes of delay per 160 train-km for flexible trains, capacity can be estimated for a range of schedule flexibility and traffic composition values (Figure 3a and 3b). Since the transformation process has been applied using the maximum allowable delay values for each type of train, there will be two different capacity curves for each traffic composition. The final ca-

capacity for a particular level of schedule flexibility is the lowest of the two capacity values for that combination of schedule flexibility and traffic composition.

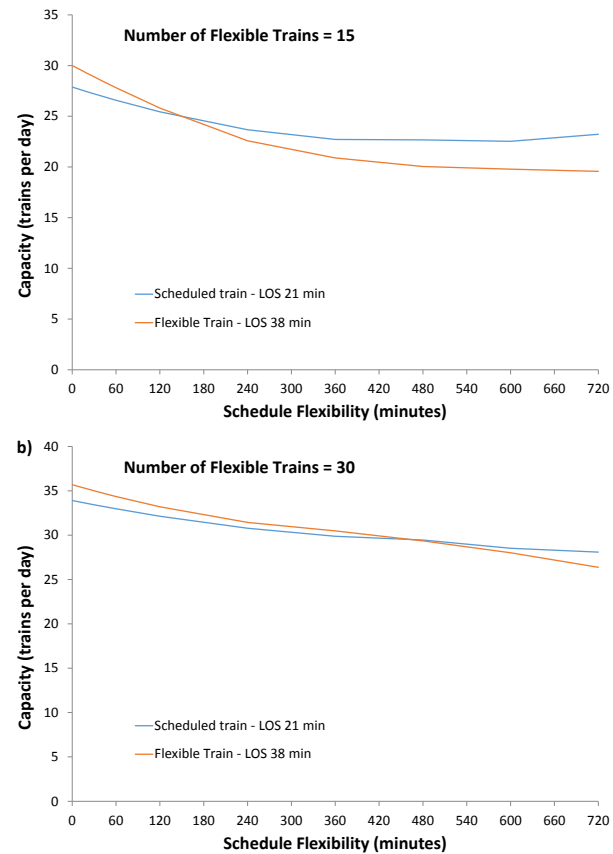


Figure 3. Final Capacity contours for scheduled and flexible trains a) 15 flexible trains b) 30 flexible trains

In general, from the relative positions of the two capacity contours (Figure 3a and 3b), the level-of-service requirements for scheduled trains defines the final contour at lower values of schedule flexibility. As schedule flexibility increases the final capacity is determined by the level of service of the flexible trains. Across the various traffic compositions, for the given train-specific levels of service, scheduled trains are less sensitive to changes in schedule flexibility compared to flexible trains.

From the perspective of the railway capacity planner, these results suggest that capacity is limited by the level of service of flexible trains if externalities and disruptions force the operations to become more flexible. However, if the operation moves toward structured operations, line capacity increases and the capacity is governed by the level of service of the scheduled trains.



4.3 Comparison of traffic compositions

Capacity values for different traffic compositions can be compared to determine the relative capacity penalty for operating various levels of schedule flexibility on different traffic mixtures (Figure 4a and 4b). Each data series represents the capacity-schedule flexibility curve for a given traffic composition as defined by the level-of-service standard for flexible and scheduled trains.

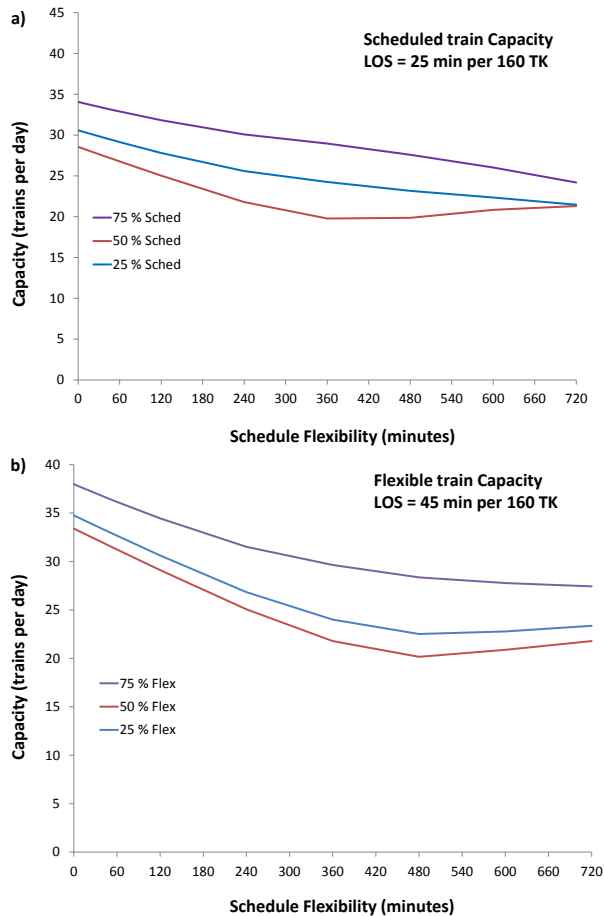


Figure 4. Capacity contours for various traffic compositions as defined by a) flexible train level of service and b) scheduled train level of service

Capacity contours defined by the level of service of flexible trains illustrate an inverse function with a decreasing slope that levels out at high values of schedule flexibility (Figure 4a). Capacity is sensitive to schedule flexibility values between 0 and 420 minutes; a move from structured operation to seven hours of schedule flexibility reduced capacity by approximately one third for all traffic mixtures. As schedule flexibility increases above 420 minutes, capacity becomes insensitive to increase in schedule flexibility.

Comparing traffic composition, the scenario with 75% flexible trains is operating at higher capacity than the 50% and 25% traffic compositions by about

five trains per day. This result may be attributed to the smaller number of high-priority scheduled trains on the line that normally cause large amounts of delay to flexible trains. The lowest capacity is obtained for the case where the traffic composition has equal numbers of scheduled and flexible trains, consistent with the previous work on train heterogeneity described in Section 2.

Capacity contours defined by the level of service of scheduled trains (Figure 4b) follow a more linear trend with less overall sensitivity compared to those defined by flexible trains (Figure 4a). For the 25% and 75% traffic compositions, consistently increasing the schedule flexibility of flexible trains makes it more difficult to sustain the scheduled train level of service, forcing capacity to continually decline.

Overall, the results consistently indicate that decreases in schedule flexibility lead to increases in capacity for various traffic mixtures.

4.4 Influence of level of service requirements

Capacity for a traffic composition of 50% was plotted across a range of schedule flexibility for various train-type-specific levels of service (Figure 5). Equivalent capacity can be obtained by certain combinations of scheduled and flexible train levels of service. For instance, the capacity curve defined by a 65-minute level of service for flexible trains and the capacity curve defined by 45 minutes for scheduled trains belong to the same population with $p = 0.05$. At this level of capacity, the scheduled trains will have, on average, 20 minutes less delay per 160 train-km compared to the flexible trains. If an operator desires an equal 45-minute level of service for both train types, the capacity would decrease substantially to that defined by the 45-minute scheduled level of service contour.

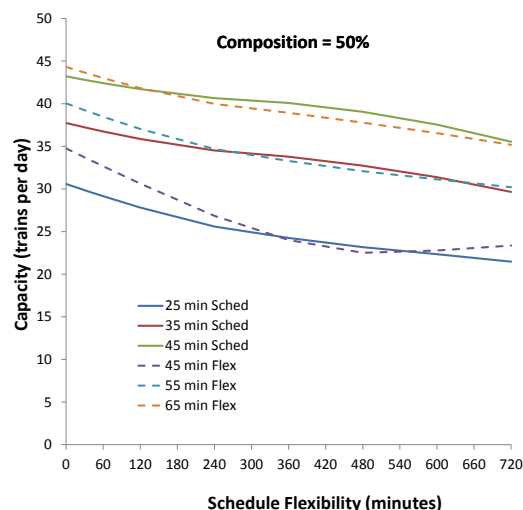


Figure 5. Capacity contours for various train-type-specific levels of service as defined by 50% composition

This change in capacity highlights the need to consider the level-of-service requirements of individual train types when evaluating line capacity. If flexible heavy haul trains are more tolerant to delays than premium scheduled services, the specific level of service provided to scheduled trains will be a better metric for establishing line capacity. Average delay across all train types does not guarantee the performance of any particular type of trains and there may be a capacity penalty for one train type at the expense of another.

4.5 Volume of flexible trains

The previous sections have examined changes in capacity due to schedule flexibility under the assumption that traffic composition remains constant. In practice, a heavy haul operator can reduce both the schedule flexibility and the number of flexible trains when transitioning to structured operations. By examining the combinations of schedule flexibility and flexible train volumes that correspond to a given average train delay (level of service), the simulation data can be transformed to illustrate the relationship between number of flexible trains and capacity (defined by a given level of service) for various levels of schedule flexibility (Figure 6).

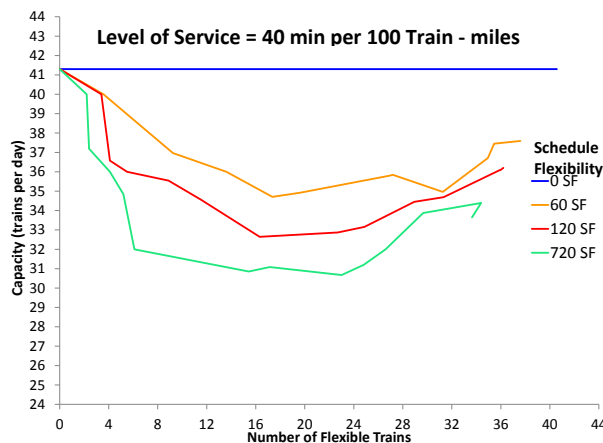


Figure 6. Capacity for various levels of schedule flexibility and number of flexible trains for a level of service of 40 minutes of train delay per 160 train-km.

Starting from a structured operation, capacity is sensitive to initial increases in the number of flexible trains. To maintain 40 minutes of train delay per 160 train-kilometres, the single-track route under study has a capacity of 41 scheduled trains per day if no flexible trains are operated. To replace twelve of the scheduled trains with flexible trains operating with 120 minutes of schedule flexibility, the capacity of the line must be reduced to approximately 34 trains per day to maintain the desired level of service. Alternatively, if the schedule flexibility of those twelve

trains can be limited to 60 minutes, the capacity only drops to 36 trains per day. The capacity of 36 trains per day can also be achieved with a high schedule flexibility of 720 minutes but only if a maximum of four of these highly flexible trains are operated on the route. It is possible to increase capacity by moving to structured operations for most trains but still operating a small number of trains with high schedule flexibility. Adjusting both the number of flexible trains and schedule flexibility gives practitioners more options for maximizing the capacity of a line through structured operations while still accommodating the flexible schedule needs of selected heavy haul trains.

Figure 6 further illustrates the increasing magnitude of capacity reduction for increasing levels of schedule flexibility. Operators can see benefits in capacity from decreasing the number of flexible trains on the line. However, to achieve a specific increase in capacity, fewer flexible trains must become scheduled when operating at lower schedule flexibility compared to operations with higher schedule flexibility.

5 CONCLUSIONS

The research presented in this study used RTC simulation to analyse the relationship between traffic volume, schedule flexibility and traffic composition. For a given constant level of service and infrastructure, different traffic compositions follow a similar trend of increasing capacity with decreasing schedule flexibility. The largest capacity gains are made when moving from low levels of schedule flexibility to completely structured operation. Routes operating with a high degree of schedule flexibility might see little improvement in capacity until schedule flexibility is substantially decreased. Practitioners may adjust both the number of flexible trains and schedule flexibility to maximize the capacity of a line through structured operations while still accommodating the flexible schedule needs of selected heavy haul trains. While schedule trains will still experience train delay, it will typically be lower than the delay experienced by flexible trains. In defining capacity, it is important to consider the specific level-of-service requirements for each train type and not just the average delay over all scheduled and flexible trains

Future work will vary the infrastructure configuration and initial timetable to better understand relationships between infrastructure, schedule flexibility, initial timetable and line capacity. Operations that temporally separate scheduled and flexible trains may exhibit different capacity relationships.



6 ACKNOWLEDGMENTS

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