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Train Delay and Railway Line Capacity Under Combinations of Structured and Flexible Operations

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TECHNICAL SUMMARY

Title

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Introduction

Many rail corridors are experiencing a transition from bulk freight trains operating on flexible schedules that maximize efficiency and economies of scale, to passenger, commuter and premium intermodal services that require more structured operations with fixed arrival and departure times. Although these premium trains receive higher priority, maintaining the schedule flexibility of bulk freight trains while simultaneously providing the precision and level of service required by passenger and intermodal trains presents a substantial operational challenge on the predominantly single-track North American rail network. The objective of this research is to investigate the behavior of routes with combinations of trains exhibiting differing amounts of terminal departure time variability, ranging from precise schedules to complete flexibility. This research seeks to characterize the relationship between the mixture of scheduled and flexible trains operating on a rail corridor, the amount of schedule flexibility in the train departure and running times, and the level of service (train delay) experienced by each of the different types of trains.

Approach and Methodology

It is common for railroad practitioners in North America to use simulation or parametric models to plan route infrastructure under flexible operations. Simulation models account for schedule flexibility by replicating traffic and infrastructure simulations for different randomized train departure patterns. While such an approach can assess the performance of an infrastructure investment under a range of scheduling assumptions, there is no guarantee that all possible traffic combinations are considered and that a true optimal solution has been found.

Parametric models do not consider schedule flexibility directly as an input but account for its effects in converting theoretical line capacity to practical line capacity. In most parametric models of rail line capacity, there is no way to adjust the level of schedule flexibility and observe the response of other variables such as delay, traffic volume, and route infrastructure.

To aid practitioners in making decisions on capacity expansion projects and developing train plans, this research seeks to develop a more fundamental understanding of the relationship between schedule flexibility, infrastructure investment, level of service (LOS), traffic mixture and capacity on single-track railway lines. By better understanding this relationship, industry practitioners can make more informed decisions on the combination of schedule flexibility, traffic mixture and infrastructure investment that meets level-of-service objectives and required line capacity.

Experiment 1: Schedule Flexibility and Mainline Train Delay

The first experiment aims to address two specific research questions: 1) For a given route infrastructure layout, what is the level of service penalty for operating a flexible schedule? 2) How much extra route infrastructure is required to support a certain amount of schedule flexibility while maintaining a given level of service?

To investigate the research questions, two different study routes were developed for experimental analysis with Rail Traffic Controller (RTC) software. The basic parameters of each route are designed to be representative of typical North American infrastructure and operating conditions. Both routes consist of 240 miles of single-track mainline with terminals at each end. Model 1 was designed to represent a minimum infrastructure condition of single track with "sparse" passing sidings initially spaced at 40 miles on-center. During the experiment, additional passing sidings were added to this route to decrease this spacing. Model 1 was simulated with a traffic volume of 24 trains per day. Model 2 was designed to represent a "dense" single track line with passing sidings spaced at 10 miles on-center. During the experiment, passing sidings on this route were connected together to form double-track segments and the route became partial double track. Model 2 was simulated with 36 trains per day. In both cases the traffic was homogeneous, comprised entirely of bulk unit freight trains. Both routes were dispatched by Centralized Traffic Control (CTC).

The overall approach of the experiment was to first establish a baseline schedule for each route (and corresponding traffic volume) that, when operated in a structured manner with no flexibility, minimizes delay for the initial infrastructure configuration of that route. Once established, schedule flexibility was introduced by allowing the baseline schedule to vary by a prescribed amount. As schedule flexibility was increased, the delay response was observed. At the same time, track infrastructure (passing sidings or double-track segments) was added to each route according to the experiment design. The resulting data allowed for quantification of the relationship between schedule flexibility and route infrastructure for a given LOS (as measured by train delay).

The experiment design included two variable factors for each model: schedule flexibility and number of sidings added (Model 1) or percentage of double track (Model 2). Each factor was simulated over a range of values or "levels" in a full-factorial design. The schedule flexibility factor established the range of departure times for each train relative to the baseline schedule. Schedule flexibility is measured in minutes and defines the time window for each random departure. For example, with +/- 60 minutes of schedule flexibility, a train that is to depart at 4 am in the baseline schedule will randomly depart between 3 and 5 am. The exact departure time within this window for each simulation trial was randomly set by the RTC software according to a uniform distribution. The schedule flexibility factor level of zero minutes corresponds to the structured baseline schedule with no deviation in departure time. For higher factor levels, the fixed departures are randomized over increasingly larger windows up to +/- 720 minutes (+/-12 hours). At this highest factor level, trains depart each terminal randomly within each 24-hour period in a purely unscheduled operation. By including these extremes, a whole spectrum of methods of operations was considered, ranging from purely structured to extremely flexible.

Experiment 2: Mixture of Scheduled and Flexible Trains

The second RTC experiment builds on the first experiment (that only considered homogeneous traffic with the same schedule flexibility for all trains) to investigate the behavior of routes with combinations of trains exhibiting differing amounts of terminal departure time variability, ranging from precise schedules to complete flexibility. This experiment seeks to characterize the relationship between the mixture of scheduled and flexible trains operating on a rail corridor, the amount of schedule flexibility in the train departure times, and the level-of-service (train delay) experienced by each type of train.

Experiment 2 follows the design of Experiment 1 but only uses the Model 1 single track corridor. To introduce schedule flexibility, depending on the desired traffic composition, an even number of scheduled trains is replaced by flexible trains (e.g. four flexible trains replace four of the 24 scheduled trains while the remaining 20 scheduled trains maintain their fixed baseline departure times). The number of flexible trains ranges from zero for the case of structured operations (all trains are scheduled) to 24 for purely flexible operations (all trains are flexible). The traffic composition factor is limited to even values to ensure an equal number of flexible trains operate in each direction. In selecting scheduled trains to replace with flexible trains, care is taken to evenly distribute them throughout each day. After introducing a given number of flexible trains, the variability of the departure times was changed according to the experiment design. For a given traffic scenario, all of the flexible trains are assigned the same value of schedule flexibility.

Experiment 3: Schedule Flexibility and Line Capacity

The results of Experiments 1 and 2 can be combined to suggest that as schedule flexibility decreases from high levels towards more structured operations, line capacity will increase. The additional line capacity obtained under fully structured operations (zero schedule flexibility) corresponds to the capacity lost by allowing some (or all) trains to operate on flexible schedules. The capacity gained by decreasing schedule flexibility can be equated to a savings in second main track infrastructure investment that would have been required to provide the same capacity under flexible operations.

Consistent with the previous experiments, a combination of baseline schedule and track infrastructure layout was developed to minimize train delay for 36 trains per day on a single-track mainline. The baseline schedule is subsequently perturbed to introduce schedule flexibility and additional traffic volume to produce the range of scenarios in the experimental design. The experiment design investigates traffic from 24 to 44 trains per day across the full range of schedule flexibility and traffic mixtures ranging from fully structured to fully flexible. To change the traffic volume from the initial baseline schedule of 36 trains per day, trains were removed and added in pairs to maintain directional balance and the structure of the "return-grid" schedule. To increase the traffic volume above 36 trains per day, an appropriate number of departure time slots used by one train in the baseline schedule are converted to depart two successive trains (departing at the minimum headway allowed by the block signal system) in the train plan at the higher traffic volume.

The results of the simulations are used to create delay-volume curves for each level of schedule flexibility and traffic mixture. By setting a required LOS (maximum train delay), these delay-volume curves can be transformed into relationships between line capacity (trains per day) and schedule flexibility.

Findings

Experiment 1: Schedule Flexibility and Mainline Train Delay

The normalized train delay values for each model were plotted to determine the LOS penalty for operating a flexible schedule on a given route infrastructure. For Model 1 on single track, all infrastructure configurations exhibit the same train delay for pure structured operation according to the baseline schedule with zero schedule flexibility. Since the added passing sidings do not match the meet locations of the rigid return-grid operating pattern, they do not improve delay for the baseline schedule. However, for Model 2 on partial double track, the different infrastructure configurations do not converge to a single point for structured operations. The added double track sections allow the baseline schedule to be executed with less delay.

The results for each corridor both exhibit a concave function with decreasing slope that levels out at high schedule flexibility. The shape of the concave function defines two general ranges of interest: low schedule flexibility between 0 and +/-120 minutes (0 and 2 hours) of variation and high schedule flexibility from +/-120 to +/-720 minutes (2 to 12 hours) of variation. In the range of low schedule flexibility, for a particular infrastructure condition, train delay is sensitive to small increases in schedule variation. For the initial single-track route in Model 1 with 40-mile siding spacing, moving from structured operations to a schedule flexibility of +/- 60 minutes more than doubles average train delay. This effect is less apparent for the partial double-track route in Model 2 but the largest increases in delay are for the initial deviations from structured operations.

As schedule flexibility increases beyond +/- 120 minutes, average train delay values become indifferent to increased variation in the departure schedule. Even in their initial configurations with minimum infrastructure, the single-track routes with 40 and 10-mile siding spacing are relatively robust to further increases in schedule flexibility beyond the initial deviations from structured operations.

By examining the combinations of schedule flexibility and infrastructure configurations that correspond to a given average train delay (LOS), the data can be transformed to demonstrate the relationship between schedule flexibility and amount of route infrastructure required for a given LOS. Examining the contour for an established LOS provides insight into the amount of infrastructure investment required to support flexible operations. For 24 trains per day and a LOS corresponding to a maximum delay of 30 minutes per 100 train-miles, the sparse single-track route with 40-mile siding spacing must be operated with approximately 30 minutes of schedule flexibility. To provide high levels of schedule flexibility above +/- two hours, six passing sidings must be added to the route. Similarly, for the same LOS at 36 trains per day, the single-track route with 10-mile siding spacing must be operated with approximately 20 minutes of schedule flexibility. To provide high levels of schedule flexibility above +/- two hours, the route infrastructure must be expanded until 50 percent of the line is double track. In both cases this is a sizeable investment in infrastructure solely to provide schedule flexibility with no increase in traffic volume or improvement in train delay.

Both Model 1 and 2 suggest a concave relationship between schedule flexibility and route infrastructure with a decreasing slope. The amount of track infrastructure required to maintain a LOS is very sensitive to initial increases in schedule flexibility. However the infrastructure quickly becomes robust to large values of schedule flexibility.

Experiment 2: Mixture of Scheduled and Flexible Trains

The train delay for scheduled and flexible trains is described by a fan-shaped set of linear relationships for each level of schedule flexibility. The linear relationships converge to a point when all the traffic is structured. As the value of schedule flexibility increases, the level-of-service deteriorates. However, there is a greater difference in train delay between the scenarios with less schedule flexibility than the cases with greater schedule flexibility.

For a given schedule flexibility, each introduced flexible train adds an equal amount of average train delay, and the value of the delay increase varies with schedule flexibility. When flexible trains are first introduced, the flexible trains experience higher values of delay than the scheduled trains. However, as the number of flexible trains increases, the delay response for both types of trains converges. When there are only a small number of scheduled trains operating on a route with many flexible trains, the delay performance of the scheduled trains is essentially indistinguishable from the flexible trains.

By examining the combinations of schedule flexibility and traffic composition that correspond to a given average train delay (level-of-service), the data can be transformed to illustrate the relationship between traffic composition and maximum allowable schedule flexibility to maintain a given level-of-service. An inverse functional relationship between schedule flexibility and number of flexible trains is observed. The amount of schedule flexibility required to maintain the level-of-service is highly sensitive to initial increases in the number of flexible trains. Equivalent delay performance can be obtained from the condition where there are a small number of highly flexible trains or a large number of flexible trains with limited schedule flexibility. From the perspective of a capacity planner, these results suggest it is possible to maintain a high level-of-service when a majority of the traffic is flexible by operating at very low schedule flexibility levels. However, the level-of-service (LOS) quickly deteriorates (train delay increases) if externalities and disruptions force the operations to become more flexible.

Experiment 3: Schedule Flexibility and Line Capacity

The results of the experiment agree with the hypothesis as transitioning flexible trains from fully flexible to structured operations increases line capacity. Further analysis suggests that the LOS requirement for scheduled trains defines overall line capacity at lower values of schedule flexibility. As schedule flexibility increases, overall line capacity is determined by the flexible train LOS requirement. Scheduled trains are less sensitive to changes in schedule flexibility compared to flexible trains.

Comparing traffic compositions, regardless of the train type LOS used to define line capacity, the highest capacity is achieved when there are fewer flexible trains and less schedule flexibility. The lowest line capacity is observed when equal numbers of scheduled and flexible trains comprise the traffic on the route, consistent with the observations of previous research on rail traffic heterogeneity. It is possible to increase line 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 their schedule flexibility provides practitioners with more options to maximize line capacity via structured operations while still accommodating the flexible schedules required by certain heavy haul trains. The capacity gained through operational changes to decrease schedule flexibility may allow railways to defer large investments in additional second main track that would otherwise be required to increase capacity.

Conclusions

For a given traffic volume and track infrastructure, train delay increases as schedule flexibility increases. However, for the corridors considered in this research, a track infrastructure condition became insensitive to further increases in schedule flexibility beyond +/- 120 minutes. Efforts to reduce delay and improve levels of service by reducing schedule flexibility show little return until operations move to highly structured conditions with little flexibility.

For a given traffic volume, a desired LOS can be achieved through different combinations of schedule variation and infrastructure according to a concave relationship. Operations that minimize infrastructure investment through structured schedules with little flexibility are sensitive to disruptions that introduce variation in departure times. Small increases in schedule flexibility require substantial investments in infrastructure to maintain the desired LOS. However, once an initial infrastructure investment is made to a certain level, the route becomes robust to further increases in schedule flexibility.

For a given constant traffic volume and infrastructure, traffic compositions with various levels of schedule flexibility yield delay curves with linear trends for both train types; incremental introduction of flexible trains causes similar increases in delay. Scheduled traffic is often delayed from its assigned departure time by inbound flexible trains at terminals, causing the scheduled train to operate like a flexible train and cascade secondary delay down the line.

From a level-of-service perspective, equivalent delay performance can be obtained from the condition where there are a small number of highly flexible trains or a large number of flexible trains each with limited schedule flexibility.

For a given LOS and a constant track infrastructure layout, different traffic compositions of scheduled and flexible trains exhibit the 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. Mainlines operating at high levels of schedule flexibility do not experience increased capacity until schedule flexibility is substantially decreased to near-structured operations. The number of flexible trains and level of schedule flexibility can both be altered in combination to increase line capacity while still accommodating the flexible schedule needs of selected heavy haul trains. Although scheduled trains are still subject to train delay when a small number of highly flexible trains remain on the corridor, the average delay experienced by the scheduled trains will typically be lower than the average flexible train delay. In defining line capacity, it is important to consider the specific LOS required by each type of train and not just the average delay over all scheduled and flexible trains.

The capacity gained in transitioning from fully flexible to structured operations on a single-track mainline can also be obtained through equivalent investment in capital projects to expand mainline track infrastructure. Depending on the exact route and traffic conditions, the amount of new passing siding and second main track construction that can be avoided or deferred can be substantial and justify cost increases required to ensure that trains adhere to precise schedules.

Recommendations

Further research is required to quantify the cost trade-off between schedule variation and infrastructure investment for a given rail line capacity. Hypothetical relationships based on the results of this research suggest that under certain conditions, total railroad costs may be minimized though a compromise between schedule flexibility and infrastructure investment. Other conditions may favor purely flexible or purely structured operations. Knowledge of the trade-off between schedule flexibility and infrastructure investment can help railway practitioners make optimal decisions regarding infrastructure expansion and train service design.

Publications

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