Analysis of Hump Operation at a Railroad Classification Yard

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Abstract: Railroad classification yards play a significant role in freight transportation: shipments are consolidated to benefit from economies of scales. However, the disassembling of inbound trains, the classification of railcars and reassembling of outbound trains add significant time to the overall transportation. Determining the operational schedule of a railroad classification yard to ensure that railcars pass as quickly as possible through the yard to continue with their journey to their final destination is a challenging problem. In this paper, we create a simulation model to mimic the dynamics of a classification yard and investigate the effect of two simple but practical priority rules (train length and arrival time) for the sequencing of inbound trains through the humping operation. We monitor the effect of these rules on performance measures such as average wait time (dwell time) at the yard and daily throughput as the complexity and frequency of the trains vary. We run the simulation on four data sets with low and high complexity of trains and low and high frequency of trains.

1 INTRODUCTION

Classification yards take the role of hub in railroad networks. Shipments are consolidated to benefit from economies of scales and full journeys are fragmented in shorter journeys, which might include one or more classification yards. Classification yards add time to the total length of the journey, in many cases idle time. Bontekoning and Priemus (2004) state that in Europe, classification yard operations may take 10-50% of trains total transit time.Dirnberger and Barkan (2007) pointed classification yard as an area of high potential for total transit time improvement. However, there are a number of working components in the operation of a classification yard that can lead to challenges in its potential optimization. In particular, the humping sequence as it is most crucial and directly influences the outbound trains departure times, Jaehn et al. (2015). Eggermont et al. (2009) noted the hardness of train rearrangement even in the most simple layouts. There are two types of classification yards: flat and hump. On hump yards there is track on a small hill over which a hump engine pushes the cars, which are then directed using switches to the appropriate classification track. Our study concentrates on hump classification yards. Armstrong (1990) provide a throughout description of railroad operations.

For the purpose of analysis, following we provide a concise description of a hump classification yard and its most salient operational characteristics. Most classification yards have three major sections, shown in Figure 1, that make up its structure: the receiving area, the classification area, and the departure area. Each region of the yard plays a role in moving the cars to its respective terminal. Once an inbound train is received, the train is directed to an available receiving track for inspection. During this time, the locomotive is removed from the train and the railcars are processed in the receiving area.

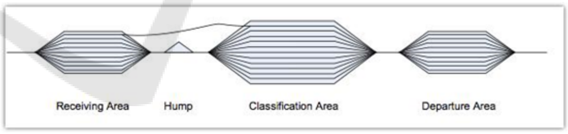

Figure 1: Layout of a typical classification yard.

After inspection is complete, the cars are approved for transfer into the classification area. In order to reach the classification tracks, an engine is used to propel the railcars from the selected receiving track over the hump towards the classification area. Cars that are enroute to the same destination are grouped together to create a block. A number of switches are used to move blocks from the hump to the appropriate classification track. An ideal situation would be for each block to have its own classification track. However, due to capacity limitations of the yard, multiple blocks may be required to use the same classification track.

The classification area stores the inventory of

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rail cars available for assembly into outbound trains. Once the predetermined amount of railcars needed for an outbound train become available, an engine will move into the classification area. The engine will then take the necessary blocks from one or more tracks and arrange them in a distinct order. After the cars are lined up in the appropriate order, the newly assembled outbound train is pulled into an available departure track. It is at this point that the locomotive is reattached and a final inspection of the railcars is completed before the outbound train leaves the departure area.

Railroad yard operations are focused on making connections between inbound trains and outbound trains. The yardmaster is responsible for generating a plan that manages these movements while ensuring that all operational constraints are met. Our goal is to characterize the effect of simple but practical priority rules such as FIFO (first in first out) and total hump time on yard performance measures such as average wait time and daily throughput as the complexity and frequency of the train vary. The sequence in which trains are hump has a downstream effect on the outbound trains. That effect can be soothed or amplified by characteristics of the flow of inbound trains as well as operational constraints of the yard such as the number of classification tracks. The rest of this paper is organized as follows. In 2 we review prior optimization work on railroad operations and on sequencing at the hump in particular. In 3 we survey the classification yard operations and present a discrete-event simulation model. In 4 we describe four data sets of inbound trains with distinct characteristics in terms of the complexity of the inbound trains and interarrival rate. In 5 we characterize the effect of the priority rules on yard performance measures such as average wait time (or dwell time) and daily throughput. In addition, we discuss how these insights can modeled operational decisions in train sequencing. 6 provides concluding remarks and directions for future research.

2 LITERATURE REVIEW

Optimization of railroad operations has received revived attention in the last years. The Railway Application Section (RAS) from the Institute for Operations Research/Management Science (INFORMS) has contributed to direct operation research (OR) academics and practitioners' attention to challenging problems in the field (INFORMS, 2015). Since 2010 each year RAS has partnered with leaders in the field to sponsor research competitions on challenging questions in railroad operations. Railroad yard operation in particular was their 2013 challenge problem. Earlier works on this problem had mostly focused on high-level analytical models; these initiatives in contrast seek to drill down to the specifics and provide detailed solutions to these operational decisions.

Boysen et al. (2012) provides a thorough review of the literature in the last 40 years. The focus is on sorting strategies and identifying research opportunities in the field. The work presented in this paper closely relates to Kraft (2002), He et al. (2003), Hansmann and Zimmermann (2008), Márton et al. (2009), and Jaehn et al. (2015) as it concentrates in the detailed scheduling decisions for disassembling and reassembling of trains. He et al. (2003) propose a mixed 0-1 programming formulation and a decomposition optimization solution method to determine the optimal decisions. They consider a model with a single hump engine and with set outbound train schedules. Their model objective is to minimize train delays and departures from the outbound train schedule. While Márton et al. (2009) combine an integer programming approach and a computer simulation tool to successfully develop and verify an improved classification schedule for a real-world train classification instance. They derive the scheduling program from a bitstring representation which it includes all the restrictions from a Swiss classification yard. Jaehn et al. (2015) investigates also the optimal humping sequence in order to minimize a weighted tardiness of outbound trains. They show that the problem is NP-hard and present a mix integer programming formulation.

Describing earlier work, Cordeau et al. (1998) presents a survey of optimization models for the most commonly studied rail transportation problems. A whole section is dedicated to analytical yards models highlighting the importance of the problem in railroad operation. In the majority of the papers reviewed by the authors, the model of choice is a queuing model and the main objective is to understand the impact of different strategies on the transit times at a policy level.

Keaton (1989) explains that car time in intermediate terminals occurs in classification and assembly operations and while waiting for the departure of an outbound train, but also as a result of yard congestion. Earlier, Crane et al. (1955) presents an analysis of a particular hump yard and discussed the queuing processes identified in inspection and classification operations. A model for the location of a classification yard was proposed by Mansfield and Wein (1958). Petersen (1977a,b) develops queuing models to represent the classification of incoming traffic and the assembly of outbound trains. In these queuing models, the author observed that the delay between end of classification to start of assembly is a minor source of yard congestion in comparison with classification and assembly operations. A thorough description of railyards is presented in the first paper.

Turnquist and Daskin (1982) models yard operations from the perspective of freight cars and developed queuing models for classification and connection delays that consider individual cars as the basic units of arrival. Martland (1982) described a methodology for estimating the total connection time of cars passing through a classification yard. The model is based on a function, fitted using actual data from the railroad, that relates the probability of making a particular train connection to the time available to make that connection and other variables such as traffic priority and volume.

In terms of sorting strategies and block-to-classification track assignment, Siddiqee (1971) compares four sorting and train formation schemes in a railroad hump yard. Yagar et al. (1983) proposes a screening technique and a dynamic programming approach to optimize humping and assembly operations. They propose an algorithm consisting of two main components: a screening technique and a detailed cost minimization procedure for the humping and assembly phases. Daganzo et al. (1983) investigated the relative performance of different multistage sorting strategies. In multistage sorting, several blocks are assigned to each classification track, and cars must be resorted during train formation. More recently, in multistage sorting Jacob et al. (2011) develops a novel encoding of classification schedules, which allows characterizing train classification methods simply as classes of schedules. Avramović (1995) models the physical process of cars moving down the hump of a yard. This process is represented by a system of differential equations that incorporate several factors, such as hump profile and rolling resistance, affecting the movement of a car.

The simulation model presented here draws from some of the findings presented in these earlier papers. Yagar et al. (1983) also considers a FIFO strategy for the humping; however, it does not investigate how the performance of each strategy is correlated to the flow of the inbound trains. The purpose of the analysis here goes beyond proposing priority rules to understand the dynamics of the flow of trains jointly with the priority rules. In order to concentrate our attention, we have decided to relegate for now aspects such as sorting decisions (Daganzo et al., 1983) and distribution of times (Martland, 1982).

3 HUMP OPERATION AND SIMULATION MODEL

The operations of a classification yards is modeled using a discrete-event simulation model. Given a flow of inbound trains, the model determines when incoming trains are humped and moved through the yard to outbound trains. There is no outbound train schedule pre-defined, the outbound train schedule is defined by the model and the decisions made in the process.

The model is based on the following assumptions:

- The classification sequence of the inbound trains. When the number of inspected trains in the receiving yard exceeds one, the model determines which train should be humped next. This is especially important to ensure that incoming trains find an open receiving track while grouping the necessary blocks for the outbound trains. Shortest trains require less time to hump which frees up receiving tracks quicker but limits the construction of outbound trains.
- The assembly sequence of the outbound trains. When the number of cars to form a unit or combination train in the classification area exceeds a certain number (minimum number of cars determined by the operational constraints), the pullback engine can assemble the string of cars into an outbound train. When there are multiple potential outbound trains, the model has to determine which train to pullback. In the given specifications there are two identical pullback engines, so while the model determines which engine pulls the train it is not critical for the operational plan.

In our model, there are additional operating characteristics that were established beforehand:

- Scheduling is non preemptive. Once a humping job is started it cannot be interrupted until all the railcars in the train have been completely humped. Similarly, the assembling of outbound trains cannot be interrupted; all tracks that will form the outbound train must be pulled sequentially and without delay between pullbacks.
- Block-to-track assignment is dynamic. Blocks are assigned to tracks as they are necessary. Empty tracks become available immediately to whatever block requires them.
- Block-to-track assignment follows a decreasing order. When multiple classification tracks store the same block type, new cars are first assigned to the track with the highest inventory up to reach capacity. Similarly, when a track of a block type needs to be pulled, the track with the most railcars is pulled first.

Table 1: Operational Constraints.

Receiving tracks (capacity)	10 (185)
Classification tracks (capacity)	42 (60)
Departure tracks (capacity)	7 (207)
Inspection time	45 min
Hump rate	2.2 cars/min
Interval between humping jobs	10 min
Hump engines	1
Pullback engines	2

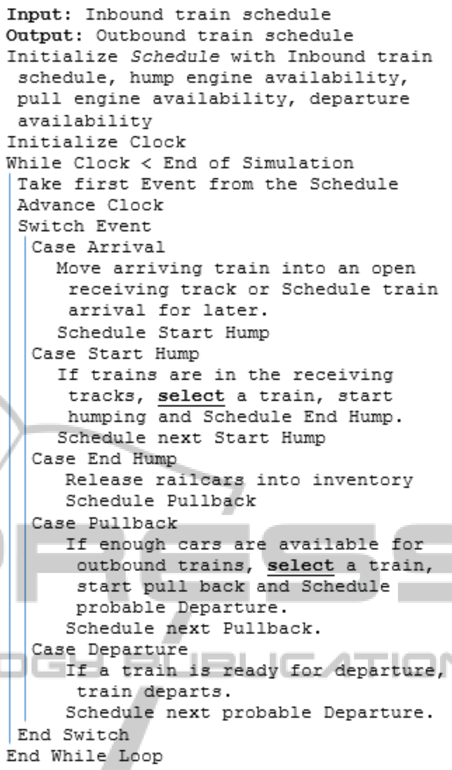
- Hump and pullback engines cannot be idle while trains wait. While theoretically engines could await for better trains to hump or pull back, in our model that is not allowed. If the hump engine becomes available and there are trains waiting in the receiving area, the engine must immediately start humping the next train. Similarly, if a pullback engine becomes available and there are enough railcars to form an outbound train, the engine will commence to pullback the available unit or block combination.

Other operating constraints such as the number of receiving, classification, and departure tracks, inspection time, and interval between humping jobs are shown in Table 1. In the next section, we briefly describe some characteristics of the inbound trains in each dataset. Figure 2 highlights the core of the simulation model where a Schedule list keeps track of each of the events that take place and a Clock subsequently advances as the simulation progresses.

There are train arrivals, humping, pulling and departures that interact through state variables such as the state of tracks, engine and location of railcars. In this simulation model, there is one spot time when a decision -select a train- with consequences that will cascade through the system take place. For those decisive moments, we identify some decision rules. We develop rules for prioritizing the humping of trains in the receiving area and the construction of outbound trains. These guidelines determine the order that inbound trains should be humped when more than one train is present in the receiving area, the classification tracks required to pull the selected block combination, and secures the necessary inventory for outbound train departure.

Humping Rules:

We concentrate in two simple but practical criteria: the idle time in the receiving area and the humping time required by the train. The idle time in the receiving area represents the amount of time that the train has been ready (after inspection) and waiting for humping while the humping time is a function of the train length. The idle time can be used as a first in first out (FIFO) criterion. This queue discipline is often referred as the fairest as it achieves the lowest variance in waiting times. On the other hand the hump time can be used for a shortest train first criterion or longest first criterion. The rationale for Shortest Train First is that an inbound train in the receiving area, regardless of the length, occupies the entire receiving track, and under certain circumstances humping shorter trains first to quickly free up a track for incoming trains might yield a decreased chance of rescheduling inbound trains and improving performance measures. A disadvantage to humping the shortest train is its eventual limitations to generate outbound trains due to a lack of acceptable block combinations. Similarly, the rationale for Longest Train First is longer trains increase the number of potential outbound train combinations that will be available in the next stage of the rail yard.



```
Input: Inbound train schedule
Output: Outbound train schedule
Initialize Schedule with Inbound train
 schedule, hump engine availability,
 pull engine availability, departure
 availability
Initialize Clock
While Clock < End of Simulation
 Take first Event from the Schedule
 Advance Clock
 Switch Event
  Case Arrival
    Move arriving train into an open
     receiving track or Schedule train
     arrival for later.
    Schedule Start Hump
  Case Start Hump
    If trains are in the receiving
     tracks, select a train, start
     humping and Schedule End Hump.
    Schedule next Start Hump
  Case End Hump
    Release railcars into inventory
    Schedule Pullback
  Case Pullback
    If enough cars are available for
     outbound trains, select a train,
     start pull back and Schedule
     probable Departure.
    Schedule next Pullback.
  Case Departure
    If a train is ready for departure,
     train departs.
    Schedule next probable Departure.
 End Switch
End While Loop
```

Figure 2: Simulation Pseudocode.

At the time of humping all ready to hump trains are given a score, *s*, that depends on the amount of time that the trains has been in the receiving area, *w*, and the amount of time that it would take to complete the hump job for the train, *l*. Both times are measured in minutes. The total score is the sum of both time multiplied respectively by an importance weight. Then, the train with the highest score is humped (discarding any train that would not fit in the classification tracks.)

Table 2: Summary Train Information.

Feature	Dataset 2	Dataset 3	Dataset 4	Dataset 5
Blocks	13	13	33	33
Inbound Trains	339	491	339	491
Trains per Day	19	27	19	27
Train Length	70	72	70	72
Total Railcars	24330	34130	24330	34130
Cars per Day	1352	1896	1352	1896
Interarrival Time	1:16	0:52	1:16	0:52
Hump Cycle	0:42	0:43	0:42	0:43
Common Block	AH	AH	AH	AH
Rare Block	BG	BG	AO	AO

$$s = \alpha * w + \beta * l \qquad (1)$$

where α and β are the respective weights.
Pullback Rules:

For pullback operations, we select the longest possible outbound train regardless the amount of time that it requires to assemble. This might be suboptimal since unit trains are faster to assemble and pull than combination trains and the gain in a longer train might be lost when the time factor is considered. Anyway, we choose this strategy since its simplicity allows to observe more clearly the effect of humping rules.

4 DESCRIPTION OF INBOUND TRAINS

Five distinct data sets of inbound trains where analyzed. Data set 1 was used to test the functionality of the simulation model. Data sets 2 and 3 have a limited number of incoming blocks (13 blocks) and block combinations (5 combinations), fewer trains per day and fewer railcars per day; whereas data sets 4 and 5 are more comprehensive with 33 blocks, more combinations (13 combinations) and more daily trains.

While the data sets had their own randomly generated inbound train combinations, there were several similarities between them. On average, the train length for each data set was approximately the same at 70 cars per train. In addition, the interarrival times of the trains were relatively consistent in its sequence. Each data set consists of 18 days of inbound trains.

As shown in Table 2, the data sets presented similar patterns within its measurements. The major differences between the data sets comes from the increased variety of blocks applicable to the full data sets. The modification in the assortment of blocks spread across the same amount of railcars in each data set causes a smaller volume of each block to be available for outbound trains. There are not notable differences between incoming trains in terms of their constitution. Most trains have at least one railcar of each block type; consequently, more blocks translate to diversified trains with few blocks of each type and longer times to consolidate the minimum number of railcar to assemble an outbound train. In other words, based on this information we expect the cycle time to assemble trains in data set 3 and 5 to be considerably longer than in data set 2 and 4. Our model will assist to define whether more emphasis should be given to wait time or the length of the train in either case.

Table 3: Summary Results 1.

	Data set 2		Data set 3	
Measure	min	max	min	max
Dwell Time	1.137	1.200	0.889	0.965
Delayed Trains	0	0	8	16
Daily Throughput	1344.69	1345.85	1818.71	1845.16
Hump Utilization	55%	56%	76%	77%
Pullback Utilization	47%	51%	65%	69%

Table 4: Summary Results 2.

	Data set 4		Data set 5	
Measure	min	max	min	max
Dwell Time	2.688	2.785	2.434	2.541
Delayed Trains	0	0	8	16
Daily Throughput	1343.24	1346.07	1820.15	1848.93
Hump Utilization	55%	56%	76%	77%
Pullback Utilization	71%	75%	87%	89%

5 COMPUTATIONAL EXPERIMENT AND CHARACTERIZATION OF RESULTS

We are going to report on a set of performance measures to compare the different priority rules. We vary the weight for wait time and hump time between -2 to 2 in steps of 0.2. A negative weight indicates that such dimension is given an inverse importance; for example, instead of longest train first, the shortest train goes first. The performance measures considered are the following:

Arrivals: On time arrivals of inbound trains are essential in order to ensure that a continuous flow of railcars is available for departure. The rescheduling of an inbound train for a later time prevents the contents of that train from being available as expected which ultimately affects other events occurring within the system. Delays evaluate how closely the simulation meets the given inbound train schedule. At the end of the simulation, the model compares the time stamps of the inbound trains to their expected arrival times. It then calculates the total number of trains that were processed and if the output matches the pre-scheduled times. This information is useful in determining how often the receiving area is occupied versus available.

Hump Engine: The hump engine plays a vital role

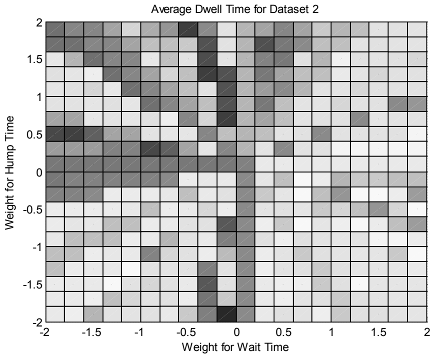


Figure 3: Dwell time Data set 2.

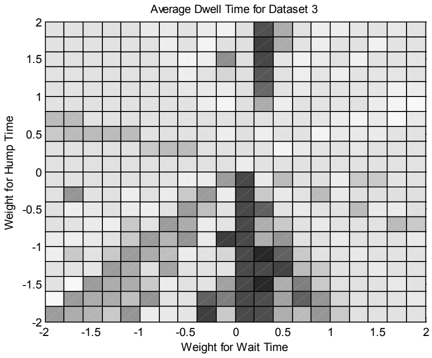


Figure 4: Dwell time Data set 3.

in limiting arrival time delays by ensuring the receiving tracks are available for future incoming trains. To accomplish this task, the hump engine should be working to eliminate the pending workload in the receiving area. By studying the waiting times of inbound trains housed in the available receiving tracks, we are about to evaluate how effectively the hump engine is working. Our objective is to maximize the utilization rate of the hump engine while minimizing the time a railcar must occupy the receiving area.

Classification Tracks: Proportion of classification tracks that are used at its peak; that is, the maximum proportion of the current tracks that are ever used. Overall average proportion of time that classification tracks are in use; that is time that used tracks are used divided by the total available time. This is only for the percentage of tracks that are ever occupied.

Pullback Engines: Expediting the removal of railcars from the classification area adds more space for incoming rail cars. The examination of the actions of the pullback engine monitors the process of eliminating rail cars within the system. In reviewing how the pullback engines are managed, we should have more data to evaluate the strength of corresponding strategy.

Departure: Once an outbound train has been pulled into the departure area, statistical data is generated in reference to its contents. Details such as the number of railcars, the block combination, and classification tracks pulled are used to gauge the characteristics of the outbound trains.

Dwell Time: Dwell time is time difference between when a rail car enters the classification track until it departs to the departure area. Satisfying our objective requires reducing the amount of time a rail car spends within the classification yard. When reviewing each simulation, the average dwell time is utilized to measure the potential benefits of the strategy in question. We started with a base case defined as FIFO priority for humping and longest train first for pullback jobs, which yield considerably good results for the four data sets in terms of average dwell time. In the data sets analyzed, the classification area has ample capacity; consequently, the main link between the humping engine and the pullback engine is through the flow of railcars that the hump engine produces in a purely downward direction. The decisions at pullback engine are not transmitted to the hump engine in an upward direction; the hump engine is safeguarded of the actions of the pullback engine thanks to the extra capacity available in the classification area.

Tables 3 and 4 summarize the results for the four data sets. When FIFO in used for humping, for Data Set 2 and 4 there are no delay arrivals and the arrival, hump engine and classification track performance measures are identical independently of the priority rule implemented by the pullback engines. In Data Set 3 and 5, about 17% of the arriving trains are delayed depending on the weights given to wait time and hump time, but again the performance measures for the arrival and classification areas are the same across the different pullback criteria. Figure 3-6 show how dwell time varies for the different weight values. The dark areas indicate the most salient performance either with lowest average dwell time or highest average dwell times. In Figure 3 and 4 we can observe some tendency and localize areas. In Figure 3 the lowest dwell time are concentrated in the vertical centered area while the highest dwell times are in the upper left corner. In other words, best dwell times are observed toward relative positive weight for wait time and negative weight for hump time. Negative weight for the hump time indicates that shortest trains are given priority over longer trains. In Figure 4, the lowest dwell times are also observed in the center area but only on the lower part. On the lower left corner and center upper are dwell times are at their highest.

Figure 5 also shows some distinctive areas. Here there is no central dominating area. The lowest dwell

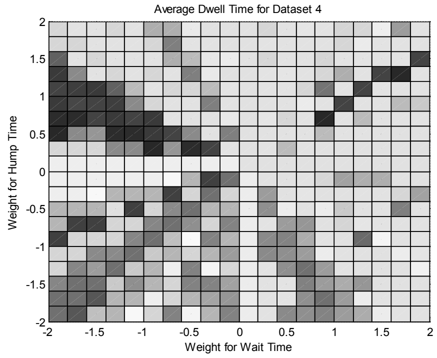


Figure 5: Dwell time Data set 4.

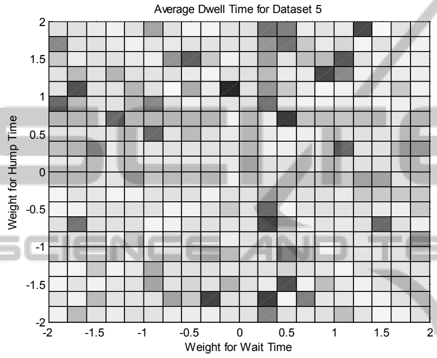


Figure 6: Dwell time Data set 5.

times are in the upper area (higher weight for hump time) and highest dwell time in the bottom area. Figure 6 does not show such distinctive pattern which indicates that as the complexity of the inbound trains increases simple priority rules such as FIFO and train length (or hump time) become more unpredictable. Interestingly, we observe that complexity as the number of blocks has a more significant impact than the frequency of trains. From data set 2 to 3 as the flow of train increases but with similar complexity the pattern intensifies. In Figure 6 some lowest dwell times are observed in the upper center area while highest dwell times are observed in the center lower area. On the other hand, the priority rule used at the hump engine determines the flow of railcars and practically defines the outbound trains and the overall efficiency of the system. There are wide differences in the performance measures across priority rules. The shortest train first yields consistently poor dwell time and high delays. However, the longest train first depending on the data set yields ranging results: for Data Set 2 it yields competitive average dwell time and throughput performance and for Data Set 4 yields the highest throughput. A disadvantage of Longest First is the variability in dwell time.

6 CONCLUSIONS

We characterize the performance of two simple priority rules -FIFO and length of the train- and their combination through a weighting function that combines them into one simple score to define the humping sequence. We observe that neither purely FIFO nor train length yield the shortest dwell times. Instead, a combination of both yields the best performance. The weights to obtain the optimal score depends on the characteristics of the flow of incoming trains. When the number of blocks is low, the optimal score gives relative importance to the wait time and negative importance to the length of the train meaning that shorter trains are given priority. These observations become even stronger when the flow of trains increases; that is, when the arrival rate of train increases. On the other hand, the optimal score gives priority to the length of the train and even a negative weight to the wait time in the receiving area when there is a larger number of blocks and a regular flow of trains. Lastly, the performance for data set 5 is very sensitive to the weights without a clear pattern toward the wait time nor the length of the trains. This further shows the importance of devising optimized priority rules for humping when the flow is high and there is great variability of trains. In data set 5, we observe that small changes in the weights can change radically whether the best or the worst dwell times can be attained. A model like the one described here can assist in the process of discovering and adjusting the weights as the flow changes. The model present here can be enhanced to analyze other yards characteristics. For example, it can assist to understand how the number of classification tracks and their capacity paces the flow of cars through the yard and the relationship between the hump and pullback jobs. In these data sets the main objective was to minimize the average dwell time while maximizing throughput; consequently, the highest achieving rules humped trains immediately and pull back trains without delay. The utilization rate of engines does not constitute a bottleneck in these problems and the engines can be freely assigned. Departure tracks are rarely full and trains spend minimum time in them. It would be interesting to analyze the upward effect of a constraining number of departure tracks. Our simulation model provides a flexible framework to test and analyze alternative priority rules for the operation of a rail yard and yields valuable insight regarding the intricate forces at play.

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