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QUANTIFYING THE IMPACT OF CLASSIFICATION TRACK LENGTH CONSTRAINTS ON RAILWAY GRAVITY HUMP MARSHALLING YARD PERFORMANCE WITH ANYLOGIC SIMULATION

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ABSTRACT

As freight transportation demand increases worldwide, railway practitioners must carefully manage the capacity of existing facilities to ensure efficient and reliable operations. Railroad gravity hump classification (marshalling) yards, where individual railcars (wagons) are sorted into new trains to reach their destination, are an integral part of the freight rail network. Efficient operation of yard processes is critical to overall freight railway performance as individual carload shipments moving in manifest trains spend most of their transit time waiting for connections at intermediate yards, with more than half of this waiting time spent dwelling on classification bowl tracks. Previous research has developed optimal strategies to allocate bowl tracks to blocks for a given set of yard track lengths. However, these strategies make simple assumptions about the performance impact of over-length blocks due to a lack of basic analytical models to describe this relationship. To meet this need, this paper develops an original hump classification yard model using AnyLogic simulation software. A representative yard with accurate geometry and operating parameters reflecting real-world practice is constructed using AutoCAD and exported to AnyLogic. The AnyLogic discrete-event simulation model uses custom Java code to determine traffic flows and railcar movements in the yard, and output performance metrics. With complete flexibility to change track layout patterns, a series of simulation experiments quantify fundamental classification yard capacity relationships between performance metrics and the distribution of track lengths, as a function of the railcar throughput volume and size of outbound blocks created in the yard. The resulting relationships are expected to better inform railway yard operating strategies as traffic, train length, and block size increase but yard track lengths remain static.

Keywords: classification yards, freight, operations, simulation, track length.

1 INTRODUCTION

In the United States, more than 1.5 million freight carloads are processed annually in classification (marshalling) yards terminating and originating an average of 6,000 freight trains per day [1]. Switching (shunting) and processing at these intermediate yards between shipment origin and destination cause yard dwell time to account for approximately 59% of the total transit time of carload shipments moving in manifest trains [2]. As such, railcar classification is a crucial bottleneck to achieving an efficient and reliable rail transportation network [3]. Accordingly, attention has been drawn to optimizing classification yard operating plans, especially strategies related to reducing the bowl idle time comprising half of railcar yard dwell time [4]. Joborn *et al.* [5] suggested that longer blocks provide economies of scale that improve the efficiency of yard switching. However, larger block sizes can become problematic when they exceed the length of classification tracks and require additional tracks to accommodate excess railcars. Meanwhile, the mainline network generates better service if each yard handles a greater number of smaller blocks; the increased number of routing options and potential for shorter connection times allows for optimized railcar trip plans [6]. There are many aspects of railcar trip and yard optimization such as track allocation,

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wagon-to-train allocation, wagon ordering within trains, plus hump, pulldown and crew scheduling, with track allocation being a common topic for decades.

Most yard research simplifies classification track assignment as a sorting problem, considering fixed track layout and geometry [7]. Mixed-integer models are widely used to optimize track assignments targeting the shortest outbound train connection time and the minimum number of tracks needed [4, 8–11]. However, classification track capacity is usually ignored given the difficulty of implementing track length in the optimization model. Only a few researchers consider track length overflow and accommodate temporary railcar storage using graph theoretical approaches [12]. Because no simple analytical model exists to evaluate yard performance under various yard infrastructure layouts, these track allocation optimization models lack the ability to properly consider block and track length distributions.

With advances in computational power, simulation has become an effective modelling methodology to estimate classification yard performance and capacity [13]. Early models used computerized and automated yard charts for manual simulation [14, 15]. More advanced classification yard simulation feature visualization and the capability to resolve conflicts. Norfolk Southern developed YardSim as a yard simulation framework to locate bottlenecks and evaluate potential changes in operating plans [16, 17]. A MATLAB model was constructed based on a hump yard in Sweden [18] to compare simulated results and field observations. In addition, SIMUL8, a computer package for discrete-event simulation, has been used to model the largest flat-switching yard in Portugal [18]. Another popular discrete-event simulation software, AnyLogic, has recently been used for simulating hump and flat-switching yards due to its flexibility in model construction [13, 19]. YardSYM, previously known as Hump Yard Simulation System, was developed specifically for hump yards and validated at multiple hump classification yards in North America [20]. In the most closely related research, Dick [6, 21] examined the relationship between yard performance and various factors including classification track length constraints and extra lines in the yard due to overflow, as a function of railcar throughput volume, size of outbound blocks, and block pattern on outbound trains. However, with little flexibility to change yard layouts in YardSYM, the influence of classification track length was not fully investigated. Although block overflow to an extra track was considered, the analytical model proposed by Dick assumed block lengths would not exceed the additional track length and require a third track. Improvements can be made to relieve these limitations and assumptions.

Because of the cost and time involved, the uniqueness of each yard layout and operation, and the overall sophistication and customization of yard simulation models, most of the models have primarily been used for business purposes and not academic research [13]. The demand is urgent for understanding and quantifying the relative impact of various factors on classification yard capacity and performance [22]. This study investigates a representative gravity hump classification yard through AnyLogic simulation experiments to quantify the effect of track length constraints under varying volume and block size distribution.

2 THE PROPOSED METHODOLOGY

A major challenge to quantifying the relationship between the distribution of track lengths and block size is that actual historical yard operating data are for fixed track layouts, and commercial software such as YardSYM features fixed track layouts. A fixed track layout makes it difficult to isolate the performance of different track length distributions for a constant traffic volume and block pattern. To overcome this obstacle, this research develops an original AnyLogic classification yard simulation model with the flexibility to independently vary the length of each bowl track. This novel yard model is used to conduct a series of simulation experiments to quantify the impact of classification bowl track length constraints on the performance of a representative North American hump classification yard.

2.1 Hump classification yard process

There are two main types of railroad classification yards: hump yards and flat yards. This paper focuses on modelling gravity hump yards, where railcars are pushed over a hill (hump) to use gravity to roll the railcars into different yard tracks as they are sorted by destination. There are three main types of hump yard layouts: inline, parallel, and mixed. This paper only models an inline hump yard; further research may consider evaluating other layouts.

In a typical inline hump yard, the receiving sub-yard, classification bowl and the departing sub-yard are usually located on the same line (Fig. 1). A hump lead and a pulldown lead connecting the three sub-yards and are generally the capacity bottleneck.

Assuming an east–west oriented yard with eastbound and westbound traffic, multiple processes contribute to the total railcar dwell time before they depart on the correct train toward their next destinations. Railcars arriving on eastbound and westbound trains both terminate in the receiving yard. However, westbound trains occupy the hump lead and conflict with normal humping operation. After arrival, the road locomotives are decoupled and sent to the road engine depot followed by crews performing arrival inspection on the remaining railcars. The westbound road engine changes direction using the arrival lead and both road engines partially occupy the hump lead and westbound arrival lead to reach the locomotive servicing depot. Once a hump engine and associated lead tracks are available, it is moved to the west end of railcars on a receiving track in preparation for the hump operation.

Once the hump is available, the hump engine pushes railcars over the hump. Each railcar is decoupled and rolls to a specific classification bowl track according to the block assembling plans. A block is a set of railcars with the same next destination that is grouped and coupled together. The railcar-block-track assignment is usually made upon arrival at the yard. However, the assigned track may be full or locked out by other operations on the other end of the track. In these cases, the car will be either sent to a spare classification track with no predetermined block plan or to a ‘rehump track’ to wait for further resolution instead. Different bowl track length distributions affect the maximum number of railcars that can fit on an assigned bowl track without requiring a spare track. Dynamically matching block and track lengths significantly increases the efficiency and capacity of the yard without changing the physical layout. With identical block length, varying the bowl track distribution could also impact the yard performance in terms of the sensitivity to volume variation.

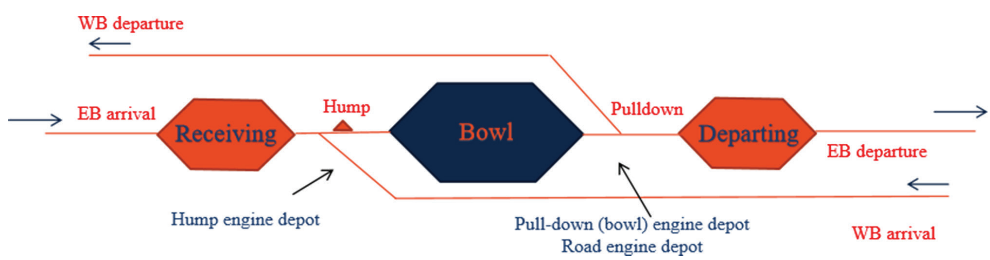


Figure 1: Schematic inline hump classification yard layout.

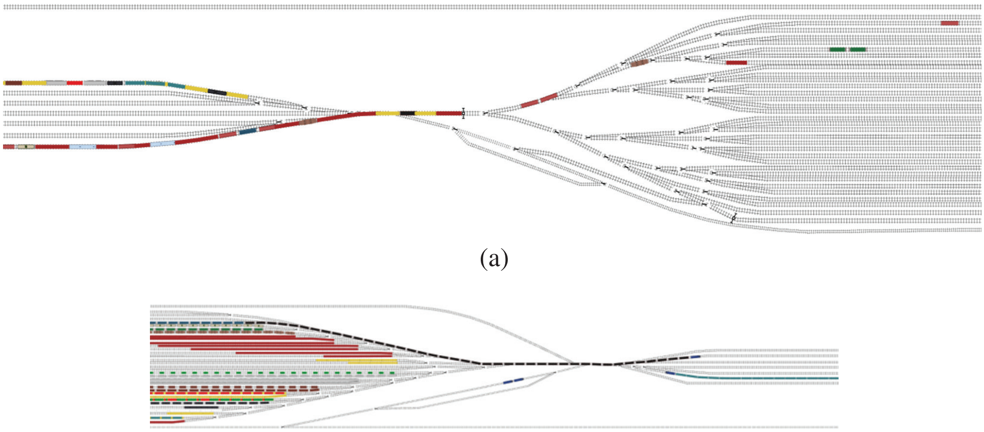
Now sorted into blocks, railcars on each bowl track will be idle until a scheduled time when they are pulled into the departure yard. This process requires availability of the pulldown engine, pulldown lead, and departure track. Once the movement begins, the crew pulls one or multiple blocks from bowl tracks, locks out each track, couples the pulldown engine to the cars, and pulls the cars clear of the bowl track (thus unlocking it) before going to the departure yard or another bowl track to be assembled into the same train. The pulldown ends when all railcars are pulled to the departure track and the pulldown engines are decoupled to return to the engine depot. With the railcars ready in the departure yard and the associated leads available, a road engine from the depot is moved to the departure track and couple to either side of the consist based on the train direction. The departure inspection is then conducted to ensure railcar connections and test the train brakes. Lastly, at the scheduled departure time and if the departure lead is available, the train departs the yard for the mainline.

This complex set of operations reveals a few challenges to realizing computer simulation, such as resolving conflicting movements on various tracks, allocating engine and crew resources, making decisions on railcar-block-track assignment and rehump at the appropriate time, and considering how yard geometry affects railcar travel speed and switch engine acceleration/deceleration and movement time. After considering multiple simulation methods and tools, a discrete-event simulation using AnyLogic was adopted for this study. AnyLogic is a multi-method simulation modelling tool, which features a rail package that allows a track layout to be constructed from AutoCAD files. AnyLogic also has the capability of generating 3-D visualizations and animations that allow researchers to monitor the yard simulation and verify that correct yard operating decisions are made by the model.

2.2 AnyLogic simulation environment

To ensure a realistic yard layout in the simulation, a representative inline hump yard with 6 receiving tracks, 33 bowl tracks, and 6 departure tracks was designed in AutoCAD. Accurate horizontal geometry for each track and related curves and turnouts were developed based on typical recent North American yard construction and expansion projects to handle 10,000-foot trains of approximately 150 railcars. The AnyLogic rail package imported and converted the AutoCAD file to rail tracks used to decide the start/end and route of train movements in the simulation model (Fig. 2). The tracks also determine the travel distances when selecting different routes. The vertical geometry was realized by assuming all tracks are level except for the hump, which allows railcars to roll freely at 3 mph down to the bowl tracks.

After building tracks, the simulation could be developed by constructing discrete-event chains shown in the pseudocode (Fig. 3). AnyLogic provides built-in modules (such as train source/dispose, train move to, and train couple/decouple) to simplify constructions of train flows. Other logic modules, including queue, hold, seize/release resources, select output, schedule, etc. can be used to realize operating decisions such as arranging tracks, avoiding conflicts, deciding which cars to couple and scheduling pulldown/departure. Each train and railcar are objects with customized features and can be moved as flow between modules. Within each module, commands are written in Java to ensure the correct movement of trains and railcars, and to collect data as needed. Other than local functions and variables inside each module, global functions and parameters calculate and store important information such as operating parameter inputs, operating plans, and current progress and performance.



(a)

(b)

Figure 2: Horizontal track geometry imported form AutoCAD with 2-D animation of railcars for (a) hump and (b) pulldown end of classification yard in AnyLogic simulation.

As the simulation runs, each module, global function and parameter display historical objects handled and the object in progress (Fig. 4 left) to help verify proper function. The simulation combines physical movements and logical flow by assigning each module a physical location on the tracks and the 'train move to' module will move the train along the track with a designed route and specific speed based on field practice to reach the next logical module. In order to avoid conflicts, tracks and turnouts were considered as resources and were virtually seized and released before and after train movements. A queue was used accordingly to ensure the 'first-in-first-out' principle of using resources. In addition to the modules, 2-D (Fig. 4 top) and 3-D (Fig. 4 bottom) animations of trains and railcars were developed to visualize the simulation and help monitor the performance of the yard.

Given the flexibility in yard layout, many yard parameters and operating settings can be studied, such as throughput volume, train arrival pattern, blocking pattern, rail vehicle speed, switch crew processing rate, track length, blockage of tracks or leads, and track assignment strategy. This flexibility is reflected in the output performance metrics. In addition to the traditional yard dwell time and outbound on-time ratio, the utilization ratio of each track, lead and crew, the idle/dwell time of each process, block length distribution, and the number of railcars sent to the spare track can all be collected for statistical analysis. AnyLogic can plot this data during the simulation to help visualize the data variations over time.

For the purpose of determining the impact of bowl track length constraints on yard performance with increasing throughput volume, in this research the variables are set as bowl track length distribution and inbound train length, while all other parameters are set constant. In terms of output metrics, the dwell and idle time during and between each process was collected to compare with previous research to validate to model. The number of railcars in the system was used to identify the start of data collection after the system warm-up. The block length distribution and average dwell time are collected and analyzed.

3 MODEL PERFORMANCE AND VALIDATION

The representative yard model parameters (Table 1) were determined from a combination of railway experience and published values. The baseline scenario includes 16 inbound trains

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Input: Inbound train schedule, outbound train schedule, train assembly strategies (rehump schedule and pulldown
schedule), yard operation parameters (number of hump engines, number of pulldown engines, motion speed,
acceleration/deceleration, etc.)
Output: Yard performance metrics (average dwell time, average bowl idle time, rehump cars, OTO (On-Time
Originations))
Initialize: Schedule Inbound train arrival, schedule Pulldown starts, schedule Rehump, prepare hump engines, prepare
pulldown engines

Simulation starts
Set Time clock=0
While Time clock<Data collection period
  Event Inbound train arrival
      If receiving yard full, enter receiving queue and schedule Inbound train arrival again when any track available
    Else, assign the train to a receiving track, schedule Arrival inspection
    Schedule next Inbound train arrival according to inbound train schedule
  Event Arrival inspection
    Perform arrival inspection
    Schedule Hump
  Event Hump
    If hump occupied or no hump engine available, enter the hump queue and schedule Hump again when hump or
      hump engine available
    Else, Perform hump
      If track occupied by pulldown, send cars to re-hump tracks
      Else If track over-length, send cars to over-length tracks
      Else, send cars to bowl tracks
  Event Rehump
    If hump occupied or no hump engine available, enter the hump queue and schedule Rehump again when hump or
      hump engine available
    Else, Perform re-hump
      If track occupied by pulldown, send cars to re-hump tracks
      Else If track over-length, send cars to over-length tracks
      Else, send cars to bowl tracks
      Update rehump cars count
      Schedule next Rehump according to rehump schedule
  Event Pulldown
    If departure yard full or no pulldown engine available, enter the pulldown queue and schedule Pulldown again
      when any track or pulldown engine available
    Else, Perform coupling check and pulldown
      While block count<planned block count
        Pull the block from dedicated track to departing track
        If block also occupies over-length tracks, pull block from over-length track to departing track
        Block count++
      Update average bowl idle time
      Schedule Departure inspection, schedule next Pulldown according to pulldown schedule
  Event Departure inspection
    Perform departure inspection
    Schedule Outbound train departures
  Event Outbound train departures
    If Time clock<Scheduled departure according to outbound train schedule, Schedule Outbound train departures at
      Time clock=Scheduled departure time according to outbound train schedule
    Else, train depart, update average dwell time
      If Time clock<Scheduled train departure time+10 min, On-time train count++
      Schedule next Outbound train departures
End Data collection period
Return Performance metrics
Simulation ends
```

Figure 3: Simulation pseudocode.

arriving during every 24-hour period, bringing 1,280 railcars of daily throughput volume (80 railcars per train) that connect to a total of 16 outbound trains, each hauling one block.

Monitoring the number of railcars in the system indicates that the simulation takes around 30 hours to reach steady state from empty and idle conditions (Fig. 5). To generate more

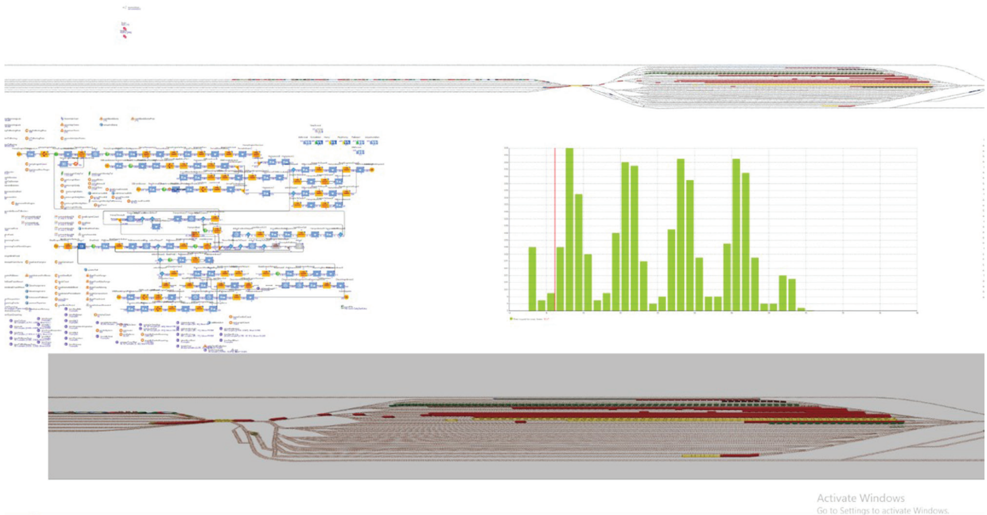


Figure 4: Simulation interface with logic flow, animations, and output statistics plot.

representative results, the warmup was extended to 48 hours before starting data collection. In terms of simulation computation time and memory usage, for the baseline scenario, the simulation executes 0.5–0.6 days of real-time operations per second, or over 150,000 steps per second at virtual speed. The software utilizes 5%–10% of the pre-set maximum of 2 GB of memory. It requires about 1.5 minutes to run simulations for the first 30 days, and an extra 1 minute for any additional 30 days. The simulation duration was selected to be 180 real-time days to balance the trade-off between longer simulation with more reliable results and longer execution time. On average, each simulation takes approximately 8 minutes.

In order to validate the simulation model and the selected parameters, the distribution of railcar idle and working time for each classification yard process step from the simulation scenario with 16 blocks and 80 cars/train was compared with a previously published time-in-motion study for a similar classification yard [2]. The simulation result indicates an average of 70.24% of terminal dwell time was spent idle sitting in the yard, compared with 71% from the published study. The similarity in the average, and distribution of idle and working time across process steps (Fig. 6), provides preliminary confirmation that the developed model is credible for the purpose of this research. Additional validation remains a future work task.

4 APPLICATION TO BOWL TRACK LENGTH CONSTRAINTS

Although yard designers attempt to match a minimum and preferred clearance length for classification bowl tracks, the geometry of ladder tracks results in different lengths for each individual bowl track. The bowl tracks in this study vary in length from 55 to 75 railcars (Fig. 7). For the baseline scenario, each of the 16 inbound trains has a constant length of 80 railcars bound for 16 destinations (blocks), or an average of 5 railcars per train for each outbound train destination. Therefore, the maximum block length should also be an average of 80 railcars, which exceeds the bowl track lengths and will require the additional spare track to temporarily store overflow railcars.

Due to randomness in inbound train composition and yard operations, the observed block length ranges from 47 to 114 railcars. If a short 47 car block is built in a long 75

Table 1: Representative inline yard design and operating parameters.

Design Parameter	Value	Operating Parameter	Value
Receiving tracks	6 (>10,000 ft)	Initial mainline speed	30 mph
Running tracks rec. yard	1	Maximum speed in the yard	15 mph
Hump engine depot	1	Hump process speed	3 mph
Hump lead	1	Train acceleration	1 ft/s^2
Block formation tracks	32	Train deceleration	0.5 ft/s^2
Rehump tracks in bowl	1	Hump engine count	2
Pulldown engine depot	1	Pulldown engine count	3
Road engine depot	1	Arrival inspection time	5 minutes + 1 minute/car
Departure tracks	6 (>10,000 ft)	Hump turnout switching interval	15 seconds
Running tracks dep. Yard	1	Pulldown coupling check time	2 mins + 12.5 second/car
		Departure inspection time	30 minutes + 1.3 minute/car
		Hump schedule	FIFO
		Pulldown schedule time	Appropriate time
		Railcar length	50 ft

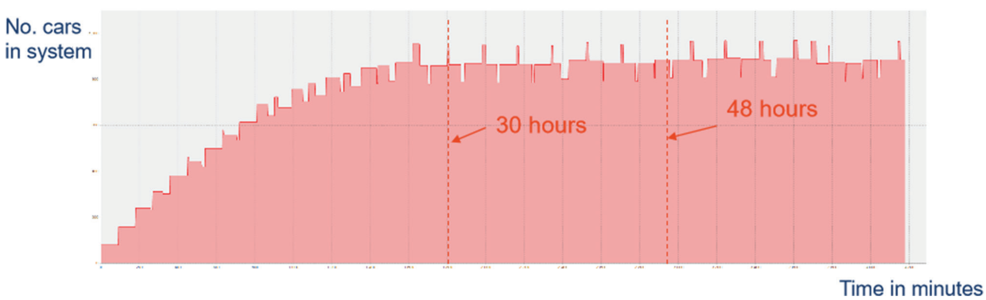
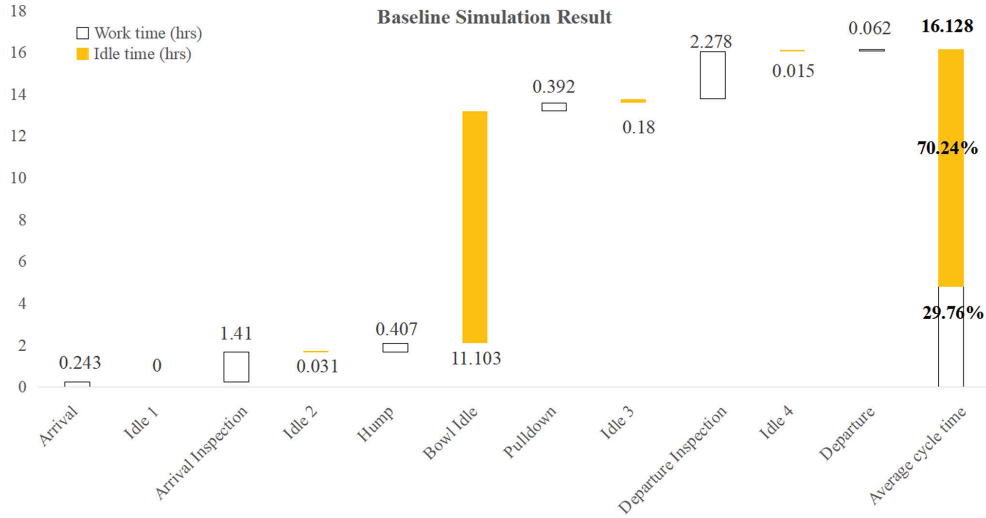


Figure 5: Number of railcars in system during simulation warm-up.

car bowl track, no spare track is needed. If a long 114 car block is built in a short 55 car bowl track, two additional spare tracks are needed, and extra movements are required to pulldown railcars from multiple bowl tracks. When block length exceeds track length, these capacity-consuming extra lines are created by the overflow, and track capacity is wasted when the block length is shorter than the track length (Fig. 7). In theory, exactly matching block sizes and track lengths should yield optimal operations, but is hardly feasible in practice. The presence of many extra lines of railcars indicates that the railcars are poorly organized with a low ‘quality of sort’ that require more effort and yard resources to combine into outbound blocks [3]. If no spare tracks are available, classification bowl



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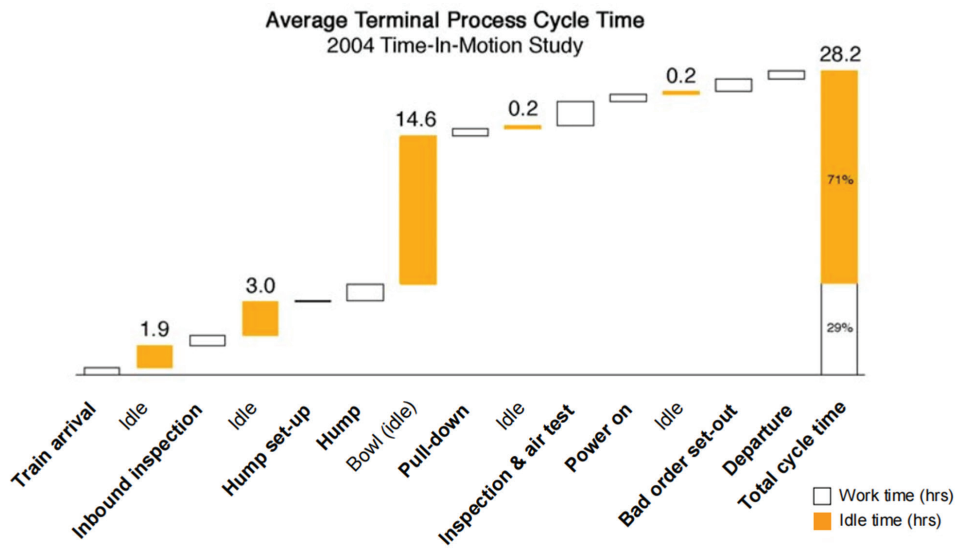

(b)

Figure 6: Model validation comparison for distribution of yard working and idle time between different process steps for (a) simulated yard and (b) published yard values.

congestion will block the hump process, and cause queuing in the receiving yard and eventually on the mainline.

4.1 Experimental design

Dick [21] proposed a numerical method to calculate the expected number of extra lines in the yard considering the proportion of time in each 24-hour period that an individual block exceeds the classification bowl track length:

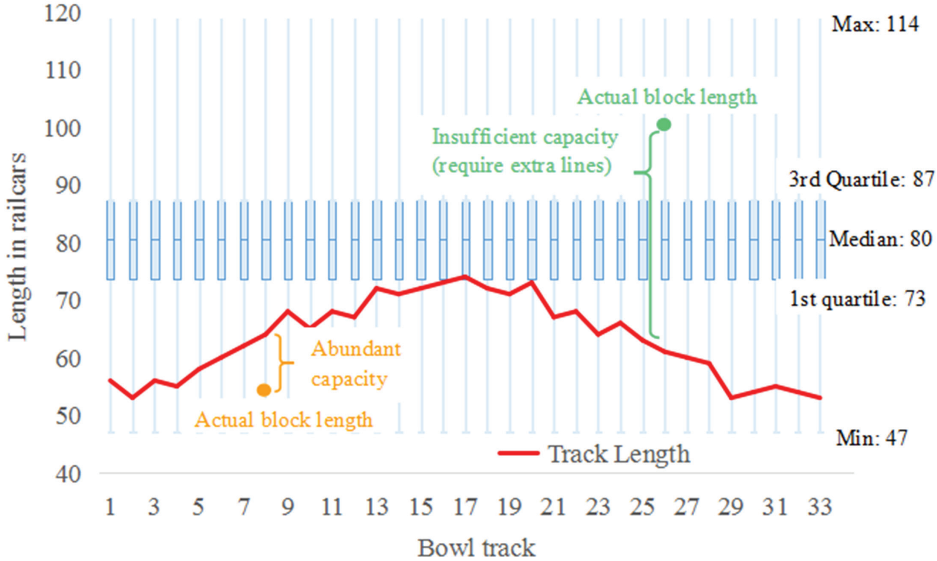

Figure 7: Boxplot of block size relative to bowl track length.

$$E(L) = \sum_{i=1}^{B} \frac{X_i}{N} \left[\frac{\frac{V}{B} - C_i}{\frac{V}{NB}} \right] . \; X_i = \begin{cases} 1 \, if \, C_i < V/B \\ 0 \, if \, C_i > V/B \end{cases} \tag{1}$$

- E(L) is the expected number of extra lines in the yard
- N is the number of inbound trains arriving per day (16 in this study)
- V is the railcar throughput volume per day
- B is the number of blocks formed in the yard (16 in this study)
- C_i is the capacity of bowl track i in railcars

However, Dick assumed that the overflow railcars for a block would not exceed the available spare track length and spill over to another spare track, forming a third line for the block. In the proposed simulation, 16 bowl tracks were used as dedicated tracks for the 16 outbound destinations, and the other 16 bowl tracks were dynamically utilized as spare tracks. Situations exist where blocks require more than one spare track and the maximum number of spare tracks available is 16. According to eqn (1), if the proportion of time for extra lines in a 24-hour period $\left(\frac{X_i}{N} \left[\frac{\frac{V}{B} - C_i}{\frac{V}{NB}} \right] \right)$ for a specific block is equal to 0.5 (indicating the block occupies 0 extra lines for half of the time and 1 extra line for the other half of the time) a full spare track is needed for this block. If the value for a block is larger than 0.5, more than 1 extra line is needed for half of the time, indicating a third track is needed. Equation (1) is thus modified:

$$E(L) = \sum_{i=1}^{B} \frac{X_i}{N} \left\lceil \frac{\frac{V}{B} - C_i}{\frac{V}{NB}} \right\rceil + \sum_{i=1}^{B} \max[0, (\frac{X_i}{N} \left\lceil \frac{\frac{V}{B} - C_i}{\frac{V}{NB}} \right\rceil - 0.5)]. \quad (2)$$

The experiments vary average block length by changing railcar throughput volume per day (V) from 60 to 180 cars/train with a step of 20. Two bowl track length distributions were proposed to quantify the relationship between bowl track length distribution and yard performance. In Distribution 1, all bowl tracks are a uniform 60 railcars in length, while Distribution 2 has tracks 50, 60, and 70 railcars long with an average of 60 railcars. For each track length distribution, average railcar dwell time in the yard was collected for 180 days. The theoretical expected number of extra tracks needed for each distribution is calculated and compared with the simulated result at the various simulated rail throughput volumes.

4.2 Simulation results and discussion

The simulations were conducted with the yard model developed in AnyLogic and the expected extra tracks for each designed scenario were calculated for comparison (Table 2). In general, as yard throughput increases, more spare tracks are used and dwell time increases. Distribution 2 has generally better performance than Distribution 1 with all bowl tracks equal in length. Although only 13.75 extra tracks are expected for the inbound volume of 180 cars per train, less than the 16 available spare tracks, the simulation breaks down for both distributions. The potential reason is that the numerical calculations assume ideal track utilization. This assumption relies on precise planning to accommodate more than one block on the same spare track with no time or track space wasted between pull-down movements. However, such efficient utilization is not feasible in practice, creating a gap between ideal and simulated capacity. In the simulation, at least two track lengths are essentially 'wasted' capacity. Future research could investigate different operating strategies that most efficiently utilize this track space to reach maximum capacity for a fixed track infrastructure layout.

Plotting average dwell time over inbound volume displays the impact of extra lines are spare tracks required on yard performance (Fig. 8). Two major increments of dwell time are observed at volumes of 80 and 120 cars per train, indicating the point where one or more blocks start requiring extra lines given the average bowl track length of 60 cars. Flatter increments are observed after 100 and 140 cars, where almost all blocks require one or two extra lines, respectively, before another line is needed.

Between the two bowl track length patterns, performance difference only exists at low and high volume. Given the same total available track length, having all tracks the same length results in worse performance around the points of requiring additional lines than having long, medium, and short tracks in the classification bowl. Since not all blocks are identical in size due to the randomness, when block size barely exceeds average track length, i.e. at the edge of requiring more lines, having different track length potentially allows for long blocks in longer tracks, avoiding additional lines that hurt the yard performance. When block size exceeds average track length by a fair amount, even assigning long blocks to long tracks

Table 2: Expected extra lines and average dwell time for two distributions.

	Distribution 1 (Equal length)		Distribution 2	
Inbound volume (cars/train)	Extra lines needed	Average dwell time (hrs)	Extra lines needed	Average dwell time (hrs)
60	0.25	15.93	0.75	15.53
80	4.25	16.55	4.00	16.52
100	7.06	18.45	6.75	18.43
120	8.37	19.09	8.75	19.04
140	12.00	19.86	11.50	19.15
160	12.37	21.77	12.00	21.40
180	13.75	Over saturated	14.00	Over saturated

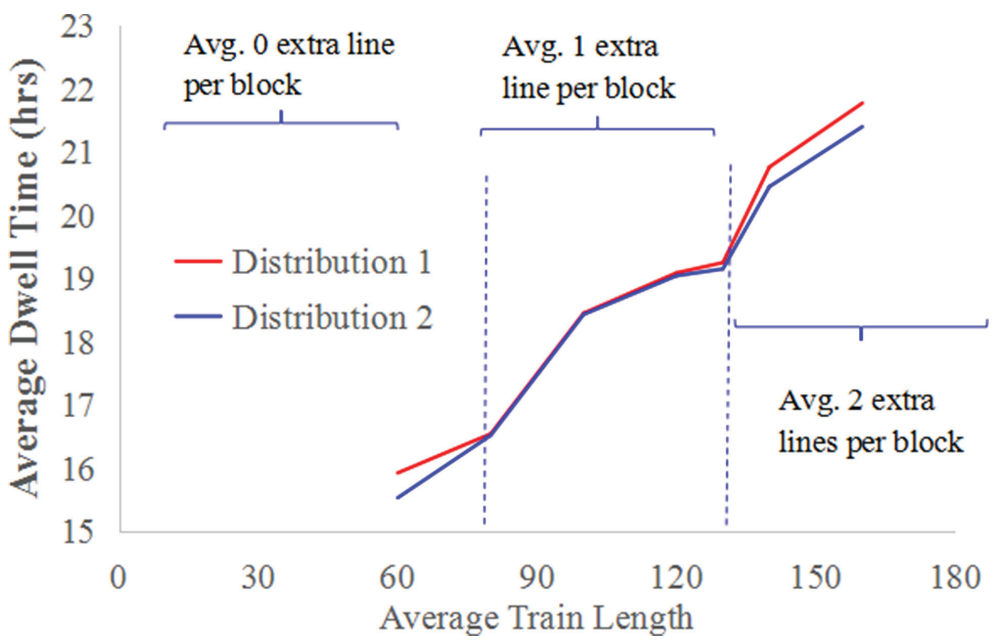

Figure 8: Effect of throughput and bowl track length pattern on average dwell time.

cannot avoid railcars, and no difference in performance is observed. These simulation results suggest a general impact of block-track assignment on improving yard performance.

5 CONCLUSIONS AND FUTURE RESEARCH

This article presents a novel simulation-based approach for performing railroad hump classification yard study, specifically quantitative analysis of the relationship between bowl track length pattern and yard performance, as a function of railcar throughput volume and the size of outbound blocks. A representative hump yard simulation model was constructed in AnyLogic with full flexibility of varying parameters and operating strategies of interest. The development of this simulation model provides possibilities for evaluating any factors influencing hump yard capacity and performance that are difficult to change or collect data from in real-world yards. Further studies can be developed to understand the interaction between yards and mainline, and between multiple yards in a network.

In terms of bowl track length pattern, this study compared expected extra lines between a numerical method and simulation results for various throughput volumes and two bowl track length distributions. It is observed that the numerical method considers optimal bowl track utilization, resulting in a theoretical maximum yard capacity. However, track space is wasted due to inefficient operating plans in the simulation and in reality. A trade-off is observed between block length relative to bowl track length in that short blocks on long tracks yields better performance but track space is wasted; assigning blocks to tracks with similar length best utilizes the track space but may cause overflow hurting yard performance. Although this study only proposed two block size distributions and the differences in yard performance are modest, the results still support the conclusion that the relative fit between the distribution of block length and bowl track length has a notable impact on yard capacity and performance in addition to yard throughput volume. The results of this paper can inform industry decisions to enhance yard operating strategy and resource utilization to promote network efficiency. Future research should include additional track size distribution, variation in block size, and multiple block-to-track assignment strategies to further quantify the impact of classification track length constraints on yard performance. Considering the similar nature of railroad yard operation internationally, this research and future studies can also inspire freight railway operators outside North America.

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