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Macro Scale Models for Freight Railroad Terminals

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Macro Scale Models for Freight Railroad Terminals

Introduction

This project has developed a yard capacity model for macro-level analysis. The study considers the detailed sequence and scheduling in classification yards and their impacts on yard capacities simulate typical freight railroad terminals, and statistically analyses of the historical and simulated data regarding dwell-time and traffic flows.

Approach and Methodology

The team developed optimization models to investigate three sequencing decisions are at the areas inspection, hump, and assembly. The optimization considers multiple engines and inspection groups. The model can be solved by existing commercial optimization solvers for one typical planning horizon, such as 24 hour. Numerical experiments and a case study based on historical data from a U.S. Class I railroad demonstrate that the proposed solution method yields better sequences and schedules, as measured by the total dwell time, compared with the practice of static sequencing. Furthermore, the results indicate that the handling capacity should be balanced among different classification steps to maximize the overall yard capacity. Furthermore, the research considers dynamic railcar planning in railroad classification yards. The plan decides the assignment of railcars from inbound trains to outbound trains under various size limitations of outbound trains and allows dynamic sequencing of inbound train classification and outbound train assembly. A mixed-integer program is presented for the problem along with a heuristic algorithm based on the harmony search strategy. Generic simulation models have been built for classification yards to understand the macro-level relationship between volumes and dwell times at yards and define yard capacity. The simulation model has been verified by the historical data from about 10 classification yards with various parameters, such as the number of tracks in each area, humps, hump engines and pull engines. The simulation mode is then used to create a large dataset to fit a general capacity model with the minimum mean square errors.

Findings

Sequence and scheduling has an impact on yard capacity. This research project finds that the handling capacity should be balanced among different classification steps to maximize the overall yard capacity. An integrated model for sequencing and scheduling in railway classification yards is proposed. Those sequences include the train inspection sequence, hump sequence, and assembly sequence. Numerical experiments with various scenarios and different numbers of hump engines and yard engines are conducted to verify the model and investigate the impact of increased capacity on the yard performance measured by the total dwell time. The numerical results show that the hump capacity and assembly capacity should be balanced in order to have a smooth and efficient classification yard operation. A case study based on a U.S. Class I railroad's historical data shows that the proposed method can help to decrease the total unconnected railcars and therefore the total dwell time compared with the current practice of static sequencing. Furthermore, dynamic sequencing can reduce total dwell time compared to static sequencing, especially when more trains are classified at a yard. Numerical experiments demonstrate that the saving of average dwell time with dynamic sequencing. However, the savings on average dwell time for each railcar become smaller when the traffic volume goes up. Once the volume through a yard is close to its capacity, the dwell time per rail car goes up very quickly as shown in Figure 1 and the benefit of dynamic sequencing diminishes. The research team also built simulation models for various yard configurations and the simulation results show a typical relationship between dwell times and yard traffic volumes (measured by the number of cars per day) in Figure 1.

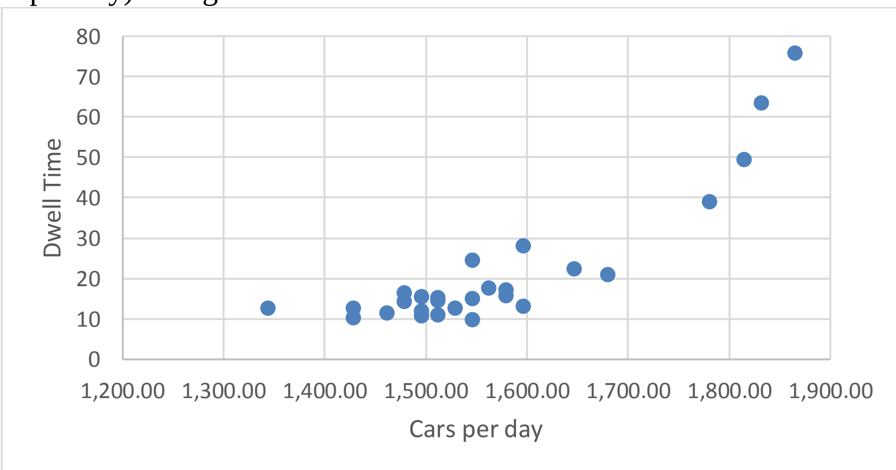

Figure 1: Dwell Time vs Cars per day

This project yields empirical models to describe the relationship between traffic volume and dwell time based on a power function for each yard. For a specific yard i that was simulated before, we can have the relationship of

$$D_i = 12.2546 + 9.5274\left(\frac{V_i}{1663.2}\right)^{16.59}. \quad (1)$$

The model fits the simulation results very well, as shown by Figure 2. Further statistical analysis shows that a yard capacity is mainly decided by the number of yard engines, the classification track lengths, and the yard configuration (single-ended vs. double-ended) have large impacts on the capacity of yards.

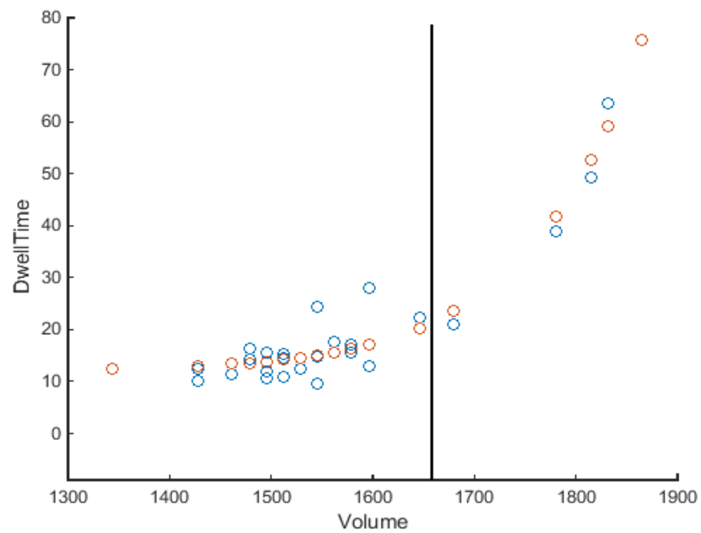

Figure 2: Compare simulation and analytical results

Conclusions

This study uses optimization, simulation, and statistical analysis to systematically analyze the capacity at railway classification yards. Better planning based on optimization techniques can help to increase yard capacity. A macro-level model describing yard capacity can help the network capacity analysis so that railroads can identify the improvement opportunities in a systematic way. Furthermore, the model may help to provide quick responses to any disruption to the network.

Recommendations

The research efforts are the first few that considers both how to use optimization in sequence, scheduling, and connection to improve railway classification yards at the micro-level and how to model the yard capacity based on yard features at the macro-level. Implementing those models in the real-worlds needs supports from major railroads. Several publications have been out of this funded research and the macro-level model will be further promoted by the research team. The team will also further pursue collaboration from railroads to calibrate the capacity models and persuade them to adopt the models for their network analysis.

Publications

H. Li, M. Jin, and S. He "Sequencing and Scheduling in Railway Classification Yards," *Transportation Research Record, Journal of Transportation Research Board*, Volume 2475, pp. 72-80, 2015.

H. Li, M. Jin, R. Song, S. He, and J. Song, "Dynamic Railcar Connection Planning in Classification Yards," Accepted by *Transportation Letters, The International Journal of Transportation Research*, 2015, http://dx.doi.org/10.1179/1942787515Y.0000000010.

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FINAL REPORT

Title

Macro Scale Models for Freight Railroad Terminals

1. Introduction

Railroads play a significant role in freight transportation to support many countries' supply chain and national security (Davis et al. 2003). Total U.S. rail freight ton-miles have doubled and density (measured by total ton-miles per mile of track) tripled between 1980 and 2006 (Systematics 2007). During the same period, total ton-miles carried by Class-I railroads increased by 93 percent (Eakin et al. 2008). The future demand for freight rail may be increased because of the growing economy and the increased consciousness on environmental issues by the public. Railroad is considered as the most environmentally freight transportation modes. On average, railroad transportation is about four times more fuel efficient than trucks, according to an independent study for the Federal Railroad Administration. Also, railroad can help to alleviate the highway gridlock, decrease the greenhouse gas emissions, and reduce the pollution (Association of American Railroads, 2015). Figure 1 provided by the Association is the change of freight rail fuel efficiency from 1980 to 2014. The efficiency increased from 235 ton-miles per gallon in 1980 to 479 ton-miles per gallon in 2014. Therefore, it is very important to improve the railroad operational performance in order to satisfy the increasing rail freight demand with limited railway capacity.

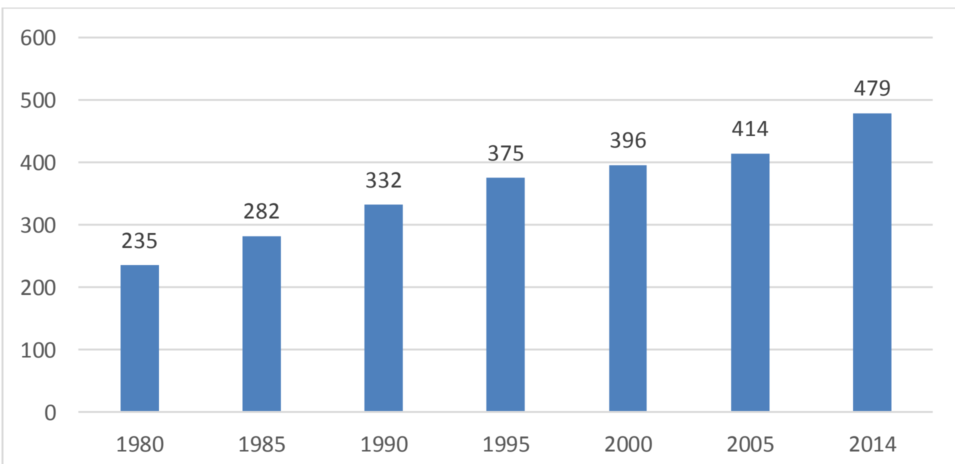

Figure 1: Freight Rail Fuel Efficiency (ton miles per gallon)

In the rail freight train transport, a freight train is consist of many railcars hauled by locomotives on a railway. Railroad classification yards are consolidation nodes in freight rail networks. In a classification yard, railcars from inbound trains are uncoupled and then assembled to generate the desired outbound trains. During the trip from its origin to its destination, a railcar spends most of its travel time in yards. In the United States, Class I railroads have an average yard dwell time of 22 hours (Railroad Performance Measures Reports, 2014). In China, railcars may spend approximately 4.5 hours in one classification yard (Annual Statistics of Transport in China, 2013). Improving yard operations could reduce the dwell time of railcars and therefore increase the overall network capacity and efficiency (Boysen et al., 2012).

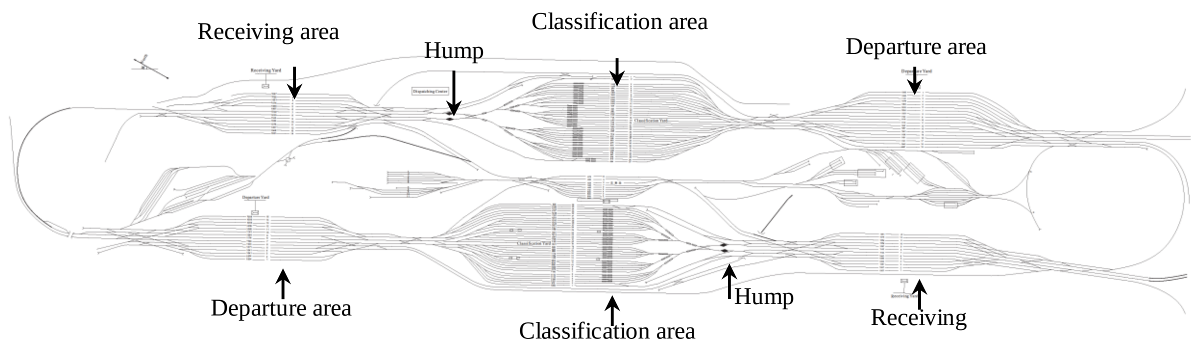

Figure 1. A typical classification yard

Figure 1 shows the layout of a typical classification yard. Most yards have one or two humping systems. If there are two, one for upward-bound traffic and the other for down bound. Each system has a hump and can be roughly divided into three main areas, which are the receiving area, classification area and departure area. The receiving area is composed of a set of tracks for storing inbound trains. After inspection and when a shunting engine is available, an inbound train will be pushed by a shunting engine over the hump to the classification area. The classification area is a collection of parallel tracks that are connected via a set of switches to the hump. Railcars are rearranged in the classification area by yard engines which pick up the railcars on one or more tracks and then assembles them in a specified order to form an outbound train. An outbound train then moves on to the departure area where it is inspected to be ready for departure.

The classification yard plays a key role in railroad freight transportation, and it is also regarded as the most complex operation in the rail transportation industry. Humping and assembling is the two main processes in the classification operation, whose functions are basically to break up and reconfigure trains. Yard operations also require various resources, such as locomotives, dispatchers, hump engines and pullout engines. According to many studies for the railroad freight industry, a rail car spends about two thirds of its system time within terminals (Reebie

Associates 1972, McKinsey & Company 1992, Logan 2006, and Mercer Management Consulting 2006). The long dwell time of rail cars in the yard is a big barrier to improve the whole rail network efficiency. Therefore, it is very urgent to study how to reduce the rail cars dwell time, then improve the rail yard operational performance. The dwell time of rail cars is strongly related to yard capacity. Due to constraints on capital, railroad companies need to make full use of the capacity. And it is estimated that by reducing the yard dwell time can result in a 15- 30% capacity improvement without a major capital investment. Also, by reducing the dwell time, it will largely improve yard productivity and efficiency, then benefit the whole rail network.

The yard capacity is measured by the maximum number of rail cars can be handled per day in the yard without significantly increasing the average dwell time. When the cars volume is smaller than the yard capacity, the dwell time is relative small, but when the cars volume is over than the yard capacity, the dwell time will increase largely. And at the same time, by reducing the dwell time, it will also largely increase the yard capacity. With smaller dwell time, the yard is sure to handle more rail cars per day. Therefore, it is very important to learn the relationship between the dwell time and the yard capacity.

Rail yard dwell time is the average time a rail car resides at a specific rail yard, and it is usually expressed in hours. The measurement begins with a train arrival event and ends with train departure. There are lots of factors causing the long dwell time of rail cars, such as the yard capacity, track numbers, and various yard operational policies. The yard capacity is usually measured by the total number of rail cars can be handled by the classification yard each day. The number of rail tracks are one of the most fundamental infrastructure of classification yard, and it was determined on the yard planning stage. Once the yard was finished, it cannot be changed easily. Therefore, we need to design the best track numbers before the yard operations. The yard operational policies mainly refer to the rule of humping sequence, the rule of block to classification track assignment, and the rule of car departure. In the following study, we will develop a Macro-level Yard Capacity Model to combine all of these factors, and their effects on the dwell time.

Macro-level yard capacity models are mainly used for railway network analysis at the strategic planning and operational planning. The macro-level models can be used to make various strategic decisions for a yard. Some sample decisions are

- Should we add one track into the classification yard?
- Should we change the assembly policy regarding which outbound train should be formed next?
- Should we add one more engine?

The answers to those questions typically require forecasting demand in the future.

Early strategic models in literature either did not consider yards at all or assumed a linear model without considering congestion. For example, the national rail planning models built by (Straszheim et al. 1971) only considered links in their routing. The shortest-path model defined on links is often used in railway network analysis (Lansdowne 1981). A generic network optimization model was proposed by (Crainic et al. 1984) to conduct strategic planning for freight rail. A yard was considered a transfer node with a fixed delay without consideration on its capacity. In recent years, more attention has been paid to the capacity analysis of a whole rail network rather than for a single yard or track. The analysis requires a well-defined yard capacity model. Sayarshad and Ghoseiri (2009, 2010), for example, proposed a formulation and a solution procedure for optimizing the fleet size and freight car allocation under given information regarding yard capacity, unmet demands, and number of loaded and empty rail-car at any given time and location. They defined capacity of a yard as the ability of the yard to receive, process, and dispatch the freight cars and assumed the capacity of each yard at each period. They did not consider the relationship between delay and volume but imposed a fixed limit on the number the railcars that a yard can process, including empty cars. (Fernández et al. 2004) formulated and analyzed a strategic model that can be used to evaluate freight railway systems, including yard operations and rail services management policies. Capacity constraints were considered for the movement of different products, depending on the availability of the type of freight cars necessary and the demands of products competing for their use. Their paper modeled yard capacity with a BPR type function, which will be discussed later.

A yard can be considered a node in a railroad node with capacity and transit time, which is perhaps based on traffic volume. In order to route all rail traffic on a network, including train design, blocking, block-to-train assignment (BTA), train routing, and timetable creation, need to consider the time and limits on those nodes. In the current literature, almost all studies only consider the capacity models at links without taking into account the capacity model at yards even though loaded railcars spend much more time in yards rather than on tracks (Turnquist and Daskin 1982). Incorporating a macro-level yard capacity could significantly enhance rail network analysis and make the network capacity estimation much more accurate, especially when the total travel time is a major performance metric for railroad service.

In recent years, railroads have started to implement optimization-based decision support systems to address various operational issues (Barnhart et al. 2000, Ahuja et al. 2007, Jha et al. 2008, D'Ariano and Pranzo 2009). However, all above models did not consider the capacity restrictions of yards in their decision makings though some of them considered link capacities. (Jha et al. 2008) provide two formulations for the BTA problem on a defined network with fixed capacity at yards measured by the number of railcars. Their results showed that their proposed solution methods for daily BTA depended on the tightness of capacity at yards. Rather than analyzing a railway network based on the capacity at yards, (Javadian et al. 2011) used a network flow optimization of the whole network to determine what the optimal capacity each yard should be. However, the paper did not really apply macro-level yard capacity models.

In summary, the yard capacity has not been widely considered in railway network analysis compared to link capacity models. Even if capacity is considered at yards, they are often assumed to be fixed with also fixed dwell time. There is a need to develop a simple yard capacity model that can capture the relationship between volume and dwell time at yards in order to evaluate capacity of a rail network and make better strategic planning. Yard capacity models developed or used in literature will be reviewed in the next Section.

The goal of yard capacity analysis is to find the optimal number of rail cars would be operated on the yard each day given some specific operational condition, such as yard infrastructure, operational cost. There are numerous researches on this problem, and different approaches and tools has been developed to deal with this problem. The earliest breakthrough is based on a single track analytical model (Petersen 1974), there was also using cycle time algorithm with traffic patterns as the input (Forsgren 2003), or algebraic approaches(Van Egmond 1999).

In many studies, the dwell time at a yard is assumed to be fixed for railcars (Crainic et al. 1984). Some studies considered the influence of train forming on the dwell time for a train. (Thomet 1971) and (Assad 1980), for example, assumed the dwell time of a train at a yard to depend on the number of railcar that the train has, as shown in (1). Their delay function at a given yard j for train i is

$$W_j + v_j x_{ij}, \tag{1}$$

where W_j is the fixed delay for processing a train through yard j, v_j is the variable delay for one rail car at yard j, and x_{ij} is the number of railcars carried by train i. They did not consider the capacity of yards at all. Their capacity model can be illustrated by Figure with a constant dwell time and a fixed capacity at a yard, which is often measured by the number of railcars or blocks.

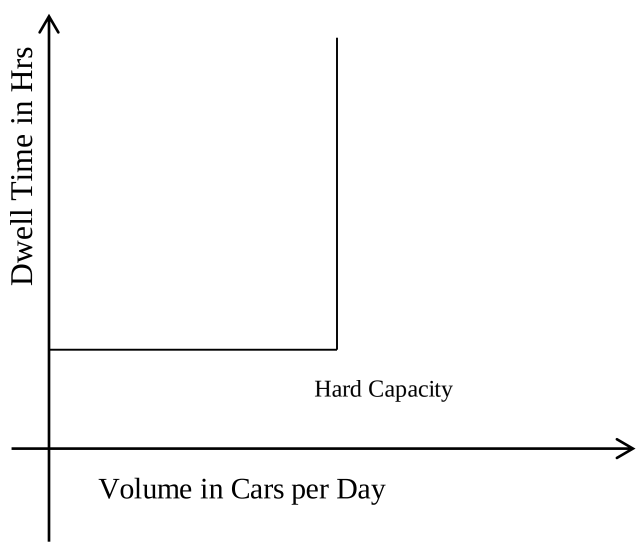

Figure 2: Yard Capacity Model with Fixed Dwell Time and Hard Capacity

In practice, however, the dwell time at a yard depends on the physical feature and operations, such as timetables of inbound and outbound trains, train connection standards, classification sequence, and block-to-train assignment, at a yard. Similar to the numerical example provided by (Petersen 1977), a sample capacity model is provided in Figure 3 to show the relationship between the average dwell time for rail cars vs. the volume through a yard. Typically, the average put-through time almost keeps constant with very little increase at the beginning when the volume increases. When the volume passes some threshold value, the put-through time increases very quickly so that the yard cannot handle any more railcars very soon. A capacity model illustrated in Figure 3 has two major parameters: the average put-through (dwelling) time before the volume reaches its capacity and the capacity, measured by rail cars per day. That threshold value can be defined as the capacity of the yard and is measured by rail cars per day.

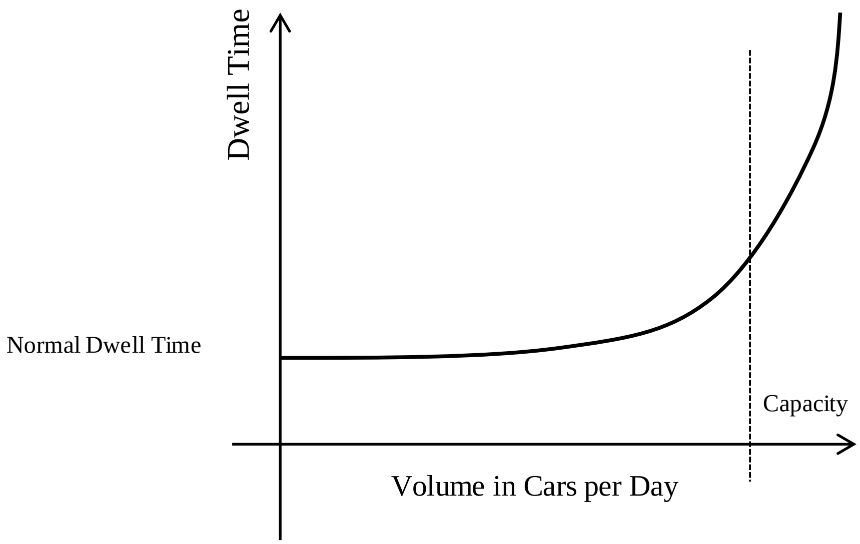

Figure 3: A Sample Yard Capacity Model

2. Approach and Methodology

The receiving and departure along with their associated inspection often are not bottleneck in a yard and take relatively constant time. Most of time in a yard for a rail car is spent on the receiving tracks waiting for classification and on the classification tracks waiting for train assembly (Petersen 1977). A queuing model can be used to model the waiting line of trains or rail cars for classification by assuming the inbound train arrivals are independent and there is only a shunting engine. Obviously, higher traffic, measured by the number of rail cars, increases the waiting time for inbound trains in the receiving area.

The train assembly process is complicated because it is influenced by both the timetable of the outbound trains and the availability of switch engines (Turnquist and Daskin 1982). Furthermore, the outbound train timetable of a yard may be influenced by traffic volume through the yard in order to form trains that are long enough. In summary, when the traffic through a yard is well under its capacity, the increase of the traffic will not significantly influence the total put-through time, as shown in Figure. However, when the traffic reaches some critical point, called capacity, the put-through time for rail cars increases very quickly so that very soon no more traffic can be routed through the yard.

We call the relationship between the put-through time and the put-though volume, illustrated in Figure, macro-level yard capacity models. The models heavily depend on the physical characteristics and management policies at the yard. Those macro-level models can be used for two major purposes at the strategic level and at the tactical level.

Both analytical models and simulation models have been used in literature to study rail yard capacity at the macro level. The two seminal papers (Petersen 1977) build two queues for analyzing a classification yard, one for the waiting line for classification and one for the connection delay. He assumed that inbounded trains arrive at the yard following a Poisson process and wait for the humping service. For hump yards, he suggested the $M/G/1$, $M/D/s$, or $M/M/s$ for the classification delay rules. If there is only one hump, the mean and variance of the waiting time for classification can be derived analytically. In Petersen's paper, he modeled the rail yard queuing system units with trains. But later, Turnquist and Daskin (1982) suggest it is more clear and convenient to consider the arrival units to be individual rail cars. Therefore, they considered a batch arrival queuing models and included the train length distribution into their model. They further derived the upper bound and lower bound of the expected values and variance of classification delays for different train length and service time distributions. They also analytically and empirically showed that the Poisson assumption for train arrivals is reasonable. The connection delay is modeled as a bulk service queue by assuming that railcars arrive from classification waiting for connection following a Poisson process and is mainly determined by the departure pattern of outbound trains. Both the expected value and variance of the time between two consecutive departures can heavily influence the connection delay. Another factor should be considered into the connection delay models is the various limits on outbound trains, such as length and weight limits of a train. However, both studies did not explicitly consider the impact of the traffic volume on the number of departing trains.

In practice, some railroads use cutoffs to decide which railcars should be assembled (Martland 1982).

- Inbound-based-cutoff: Cars with destination K arriving at time t should be connected to all outbound trains departing for destination K after time $t + C$.
- Outbound-based-cutoff: All cars with destination K arriving more than C hours before the scheduled (or actual) departure of an outbound train for destination K should make the connection.

Here, C is the cut-off time that defines the minimum scheduled time for the connection. The application of cut-off time can fundamentally change the connection delay calculation.
Service rates influence the waiting lines of both queuing models for classification delay and for connection delay. The queuing models proposed by (Petersen 1977) were verified by two hump yards owned by the CN railroad to compare the estimated put-through time distribution and actual distribution. The results showed that the assumption of queuing models worked

reasonably well regarding predicting put-through times for railcars for different destinations, perhaps because of the high variability in train and block lengths.

Though the analytical results from queuing models from late 70's and early 80's seem technically beautiful and have been verified by real-world data, they have not been well accepted by the railroad industry perhaps because of the following reasons.

1) The analytical models are complicated and require some mathematical background to understand. In some sense, the queuing models are so complicated that they are considered black boxes from the viewpoint of practitioners. Without a complete understanding, practitioners do not have confidence to utilize the analytical models.
2) Various assumptions are used during analytically modeling. Even though an assumption could be well justified based on theoretical analysis, practitioners often do not agree with the assumptions based on their real-world experience.
3) Even if a practitioner trusts all assumptions and the modeling procedures, the models are complicated and do not have flexibility to incorporate changes.

Therefore, a straightforward model to describe yard capacity and its connection with yard configurations and management policies are necessary to incorporate yard capacity into railroad network analysis and guide both strategic and tactical decisions for railroads.
To avoid above shortcomings of analytical models, simulation has been used in several recent studies. For example, (Marinov and Viegas 2009)proposed a simulation modeling methodology for analyzing flat yards and implemented it with a discrete-even simulation package, SIMUL'8, for a sample yard. (Lin and Cheng 2011) from Norfolk Southern incorporated mechanical repairs and re-humps in a simulation model for a hump yard based on a simulation framework for rail yards proposed by them earlier (Lin and Cheng 2009). The simulation model also considered train schedule of inbound and outbound trains, trip plan of railcars, and train consist with performance measures of connection, outbound train on-time percentage, resource utilization, hump count and occupancy, humping and pullback process cycle time, track utilization percentage, and terminal dwell time. Similar to (Dirnberger and Barkan 2007), the simulation model found out the pullback process, which pulls cars from the classification tracks to form outbound train in the forwarding yard, is a bottleneck.
Simulation models have strong flexibility to incorporating various factors and features at different yards and could fully consider variance without approximations. For one yard, once a simulation model is established, what-if analysis can be easily conducted by changing components in the model. However, significant efforts are involved in simulation model development for each yard. Furthermore, it is almost impossible to incorporate simulation models in the analysis of one railroad network, which often includes multiple yards and other infrastructure.

In summary, the review of the macro-level yard capacity studies shows that there is a need to establish yard capacities models with the following features.

1) The models should represent the relationship between the dwell time (put-through) time and traffic volume in railcars in a simple way so that the capacity of yards can be incorporated into railroad network analysis.

2) The models should consider the major physical characteristics and operational management at yards in a reasonably straightforward way so that practitioners could estimate capacity lines easily for individual yards.

Considering the analytical model is too complicated and not flexible, we decide to develop a simulation model to mimic the yard operation and then use the extensive simulation results to build a simplified dwell time and volume function. Our simulation model will use the rail cars as the object, and consider rail cars arrive at the rail yard in batches. Our goal is to minimize the total dwell time that an individual rail car spends in the yard from inbound to departure. Our simulation model is consist of the following six process:

1) Generate Inbound Train

Inbound trains are those that come into the rail yard from other yards, and for each inbound train, it is consist of a set of different rail cars. These rail cars are grouped in different blocks. And a block is a set of rail cars with the same destination. Every time, when an inbound train arrives, we'll assign priority order for each block of cars, the assignment is based on their outbound schedule, the earlier the outbound schedule is, the higher priority the block of cars are. In this inbound train arrival stage, we need to decide the train arrival process, the number of blocks and the size of each block. In our simulation model, we assume the inbound trains arrive at the rail yards according to a Poisson process with block of cars, the number of blocks is uniform distribution and the size of each block is triangular distribution. Let the arrival rate of the inbound train be λ , the minimum number of block is p, and the maximum number of block is q. The minimum size is x, maximum size is y, and the mode of the size is z. $N(t)$ is the number of arrival rail cars in $(0, t]$, b_i is the number of blocks in train i and s_j is the size of block j.

2) Receiving Track Assignment

We assume that each receiving track is long enough to contain a single train completely. The number of receiving tracks is n, and the capacity of receiving track i is R_i, $1 \leq i \leq n.$ The rule of receiving track assignment is that from the order of R_1 to R_n, if R_i can hold the whole inbound train i, then assign the train i to the receiving track R_i; otherwise, assign train i to receiving track R_{i+1}. In the receiving area, the inbound train locomotives are detached from the rail cars, and these yard crews would inspect the operational condition and mechanical problems for these rail cars. Let the inspection time is t minutes for each car. However, Petersen(Petersen 1977) has mentioned this inspection process is not a major bottleneck because additional inspection can be handled quickly. Furthermore, this inspection process is carried out during the time that these rail cars are waiting for humping, so it usually won't affect the total dwell time too much. In our simulation model, we assume the inspection rate is n cars per hour, so the total inspection time for each train is the number of cars multiply the inspection rate.

3) Hump Sequencing

After inspection, these inbound trains are sent to classification area. Here we need to decide the hump sequence for each inbound train. The hump sequence problem is to identify the best order for humping these arrival inbound train. And it is an important determinant of the rail yard operational performance. If the arrival rail cars are not humped on the right time, the departure time for the scheduled outbound train would be delayed. For example, an inbound train carries rail cars whose earliest outbound train schedule is t_1, and there is another inbound train who

carries rail cars with outbound time t_2. If the first train arrives earlier than the second train, but the relation of these rail cars' outbound time is: $t_1 > t_2$. So it may be better to hump the second inbound train which arrives later but carries rail cars with an earlier outbound train schedule. So in order to reduce the dwell time in the rail yard, it's essential to specify a humping sequence that ensures that the outbound trains depart from the yard on schedule.
In our simulation model, we use a priority-based method to assign the hump sequence. Specifically, according to the assigned priority during the inbound train generating. For each inbound train in the receiving area, if it carries a higher priority rail cars, then it will be sent to hump earlier. And we will compare our priority-based method with the First-In First-Out (FIFO) method, which is widely used in queuing system simulation model. The number of humping engine is h, when there are idle engines, these inbound trains waiting in the receiving area will do the humping procedure one by one. And we assume the humping rate is μ cars per hour, then the hump time for each train is the hump rate multiplies the total number of cars on the train.

4) Block-To-Track Assignment

Once these rail cars are humped, they will be sent to a bowl, which is consisted of many parallel classification tracks. Here we need to determine: for each humped rail car, which classification track should be assigned to it, and the problem is called block-to-track assignment problem. There are many factors need to be considered when do this assignment, such as the capacity of each classification track, the outbound schedule of railcars, the size of each block. Unreasonable assignment may increase the dwell time of these rail cars very much, therefore, we need to find an efficient rule to assign tracks to the blocks such that these rail cars can be pulled out with minimum time. We use a greedy algorithm to do the block-to-track assignment. From left to right, we assign index to these classification tracks 1 to N. And then the procedure is that first, if a track already has some rail cars with the same block, then assign this rail car to the track and couple with other existing rail cars; second, if there is no existing rail cars with the same block, then randomly assign this rail car to the next classification track. Ideally, each classification track only be assigned to one block, but because the limitation of the number of classification tracks, it may be necessary to allow several blocks to one classification track. Therefore, once all of the classification tracks are filled up, the additional block of cars need to be assigned to one classification track which already occupied by another block. For this case, we just assign this block of cars to the first classification track, and starting the first step again. However, it may exist the situation that a block of cars are split in multiple areas of the same track, this is called 'dirty track' (see the different kinds of tracks in figure 4). If so, those rail cars may need to be re-humped later when some of other classification tracks become available again. However, at this point of time, we won't allow the re-hump case in our simulation model.

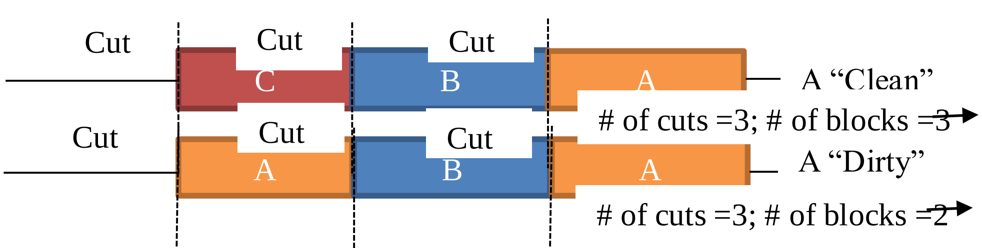

Figure 4 Cut, block, clean and dirty track definition

Higher volume often leads to more dirty tracks, which require more pullback efforts and therefore hurt the performance of the pullback (connection) process.

5) Pullout Allocation

After rail cars arrive at the classification track, pullout procedure would be carried out at once. The whole pullout procedure is that at each time, a pullout engine pulls a line of rail cars form a classification track to a departure track, and assembles with an outbound train. In our simulation model, we assume the assemble rate is p cars per hour. At this point, we need to decide two major problems: First, these rail cars should assemble with which of outbound trains? Second, which lines of rail cars at the classification track should be pulled by the pullout engine? Which means the sequence of rail cars need to be pulled from classification tracks. For the first question, it is mainly determined by the departure schedule of these block of rail cars. In practice, the outbound schedule would be specified in the rail yard operational plan, and it also points out that each outbound train will carry a list of potential blocks. In our simulation model, we achieve the block-to-train problem like this: First, we specify the number of outbound trains, and then generate an outbound time table for each outbound train. And at the time of generating a block, we randomly assign an outbound train for it.

And for the second question, it is usually determined by the sequence of the block of cars on an outbound train, which is called block standing. So the first step to do the pullout allocation is: checking the outbound schedule for each different block of rail cars. We then sort the pullout sequence according to their respective departure schedule, the earlier the departure schedule is, the higher pullout priority they are. And for the case that two or more blocks with the same outbound schedule, we choose the line of rail cars which have more individual rail cars.

6) Outbound Train Departure

Once all of blocks for a particular outbound train are assembled, these rail cars must be inspected for mechanical problems and connection. If the train is inspected with no defects, it will leave the yard from the departure track. In normal conditions, these outbound trains would depart according to the outbound schedule, which is specified in the beginning of simulation with a given time table. But in practice, it can also happen that an outbound train with scheduled time may be delayed to depart. It is usually caused by some of block of rail cars are not pulled out on time. In our simulation model, we randomly generate the out schedule for each out block, if it matches with the predefined outbound schedule, then set the block depart the yard at the schedule.

There are plenty of computer simulation tools, we can basically group them into two parts: one is free open source simulation tool, the other is proprietary.

a. Free or Open Source
   1) C++: it is an object-oriented programming language, and it was designed by Bjarne Stroustrup in 1983. C++ is famous for its speed, and is a good choice for computer simulation, which usually needs a very large run time. It is also cross-platform, and with the new c++ 11 version, it possessed many new features and an enlarged standard library. So it is a powerful and flexible simulation tool. However, it is much more complicated than other simulation tools, and you will need to write much longer code and spend more debug time to develop and maintain your simulation projects.

2) Simpy: it is an open-source discrete event simulation package based on python and was released under the MIT license in December 2002. Simpy uses the simple python generator functions to model the simulation processes and entities, such as customers, vehicles or agents. It also provides many kinds of shared resources in simulation to model limited capacity congestion points like servers, engines. Because it was developed by python, it also possesses the advantages of standard python, for example, it’s easier to develop, brief code and cross-platform. However, it also inherited the disadvantages from python, it is slow, which makes it not optimal for large simulation project.

b. Proprietary

1) Flexsim: it is a discrete event simulation software developed by FlexSim Software Products, Inc. Flexsim is mainly used in manufacturing, logistics and transportation. It is based on object-oriented design, and its objects are defined and programmed in four classes: fixed resource class, task executer class, node class and visual object class. Just like most of commercial simulation software, it is easy to use. Users just need to drag and drop the predefined 3D objects to build the model, and it has fantastic 3D animation. However, because it was developed by c++ programming language. You will need to be familiar with the c++ in order to use some of advanced features, which makes it not convenient and difficult for most of users.

2) Arena: it is a discrete event simulation and automation software developed by Rockwell Automation in 2000. It uses the Siman as processor and simulation language. In arena, users build a simulation model by placing modules as processes, and these modules have some specific actions relation to entities, flow, and timing. Another feature of arena is that it can be integrated with Microsoft technologies like Microsoft visio, excel and access. Though it has many functions, its logic is not clear. It just uses various boxes of different shapes to represent the simulation processes, and its submodal interface makes it difficult to read and improve the model. Furthermore, the use cost of it is larger than other simulation tools.

3) Anylogic: it is a multimethod simulation modeling tool for business and science, and it was developed by the AnyLogic Company. It supports agent-based, discrete event, and system dynamics simulation methodologies. Anylogic includes a graphical modeling language and also allows the user to extend simulation model with java. By java coding, it can be created as the java applets, and then be opened with any standard browser and very easy to share or place on websites. Also, it has a railyard library, which makes it efficient to simulate and visualize any kind of rail transportation including classification yards. CVS has used it to solve several railroad operation chanlleges. Also, it has free version for personal learning and educational purposes, and its simulation logic is very clear. Then it is quickly to read a model or improve it.

Based on the above comparison of various simulation tools, we choose the Anylogic to simulate the classification yard, and do the yard capacity analysis with the established simulation model. The simulation model has been verified by the historical data from about 10 classification yards with various parameters, such as the number of tracks in each area, number of humps, hump engines and pull engines. The simulation mode is then used to create a large dataset to fit a general capacity model with the minimum mean square errors.

3. Findings

In addition to simulation models, this research project also develop optimization models for the sequencing at various steps and finds that the handling capacity should be balanced among different classification steps to maximize the overall yard capacity (Li et al. 2015). An integrated model for sequencing and scheduling in railway classification yards is proposed. Those sequences include the train inspection sequence, hump sequence, and assembly sequence. The sequencing and scheduling model (SSM) developed in this research considers a classification yard that can performing inspection, hump and assemble. We assume that the arrival times of inbound trains and the departure times of outbound trains are given by the dispatching schedule *(6)*. The railcar connection plan that specifies which outbound train each inbound railcar is assigned to is also assumed to be known. In the railroad practice, it is called "Right Train, Right Car". The track assignment in the receiving/departure area are not considered in our model, because they are not usually bottlenecks *(3)(19)*. Furthermore, we do not consider classification track assignment, and we assume that the capacity of classification area is infinity. The sequencing and scheduling model has the following features: (1) a train can only be served by one inspection group or engine at any time, and (2) an inspection group or engine can only serve one train at any time. In other words, a resource (inspection group or engine) has to finish the previous task before starting the next task.

Simultaneously performing multi-tasks of inspection, hump and assembly is allowed if there are more than one inspection group, hump engine and yard engine. Figure 2(a) illustrates an example of the assemble sequence of outbound trains. The source node *s* and sink node *t* mean the dummy trains in the planning horizon; and rectangles represent the planned outbound trains. There are 3 yard engines, or pullback tracks. Both the source node and the sink node are connected with three arcs. Each train only has one arc flow in and one arc flow out. If no tasks are assigned to a yard group, one arc connects source node and sink node directly (Figure 2(b)). If there are two or more hump engines, and the dispatching rule is allowed, the hump process can perform simultaneously. While, for most of the classification yard, only one train humped each time, as it is easier to ensure security. The confliction of simultaneous processing dose not considered in this paper.

Assume n inbound trains are expected to arrive during the planning horizon with a_i as the known arrival moment of inbound train $i,\ i = 1, \ldots, n$, where a_i's follow an ascending order. Each inbound train i is first inspected with the amount of time of t_i, which usually depends on the train length, and then waits in the receiving area for humping. The hump time for inbound train i is assumed to be h_i, which also often depends on the train length. For the modeling convenience, we add two dummy inbound trains, that is $i = 0$ and $i = n + 1$ respectively. At the same time, there are m outbound trains are scheduled to leave during the planning horizon with d_j as the scheduled departure time of outbound train $j,\ j = 1, \ldots, m$, where d_j's also follow an ascending order. Denote b_j as the inspection time of outbound train j, and v_j as assembly time of outbound train j. Similar to the inbound trains, there are two dummy outbound trains, $j = 0$ and $j = m + 1$. Assume that τ, π, ω and φ are the sets of inbound train inspection groups, hump engines, yard engines and outbound train inspection groups respectively.
A cut, indexed by u, is a group of railcars that move as a single unit from their origin to their destination and also stay together within the yard to facilitate the humping processes. The set of

cuts belonging to inbound train i is denoted by U_i and the grand set of $U = \bigcup_{i=0,\dots,n} U_i$ is the set of all cuts during the planning horizon. Here, U_0 is the set of cuts that have been in the classification area at the beginning of the planning horizon. According to the departure schedule and railcar connection plan, we know the possible cuts that can be assigned to outbound train j. So we define U^j as the set of cuts that outbound j can carry. All cuts assigned to outbound train j should be ready at classification tracks before the assembly of outbound train j starts, and a minimum buffer time T is required for a cut to be connected after it is classified.
The scheduling problem makes the following major sequencing decisions.

1) The inspection sequence of inbound trains, o_{ik}, which is 1 if inbound train i is inspected immediately before inbound train k and both trains are inspected by the same inspection group, and is 0 otherwise;
2) The classification sequence, p_{ik}, which is 1 if inbound train i is classified immediately before inbound train k by the same hump engine and is 0, otherwise;
3) The assembly sequence, q_{jl}, which is 1 if outbound train j is assembled immediately before outbound train l by the same yard engine and is 0, otherwise;
4) The assignment of cuts, x_u, which is 1 if cut u is connected during the current planning horizon, and is 0, otherwise;
5) The inspection sequence of outbound trains, w_{jl}, which is 1 if outbound train j is inspected immediately before outbound train l and both trains are inspected by the same inspection group, and is 0, otherwise;
6) The starting time to inspect inbound train i, starting time to classify inbound train i, starting time to assemble outbound train j, and starting time to inspect outbound train j are denoted by θ_i, r_i, s_j, and ϑ_j respectively.

The objective of the yard master is to depart as many railcars as possible during the current planning horizon. Due to the “right car, right train” practice, all un-departed (i.e., un-connected) railcars may need to wait for about 24 hours or more than 24 hours in the yard until the next “right” outbound train. This objective is equivalent to the goal of minimizing the total dwell time, which is often used to measure the service level for railroads. For example, the six US Class I railroads publish their yard dwell times at major terminals weekly at http://www.railroadpm.org/. Therefore, the objective function of the proposed model is to minimize the total dwell time, which is $\sum_{u \in U} \delta_u \cdot \Delta_u \cdot (1 - x_u)$. Here, Δ_u means the additional dwell time (usually 24 hours) of cut u in yard if it cannot be connected to the right train in the current planning horizon.

Based on the problem statement and notations above, we propose the following mixed integer program as the SSM.

SSM: max $z = \sum_{u \in U} \delta_u \cdot \Delta_u \cdot x_u$ (1)

s.t.

$$r_k - (r_i + h_i) \geq M \cdot (p_{ik} - 1) \qquad i, k = 1, \dots, n, i \neq k; \tag{2}$$
$$r_i - \theta_i - t_i \geq 0 \qquad i = 1, \dots, n; \tag{3}$$
$$\theta_i - a_i \geq 0 \qquad i = 1, \dots, n; \tag{4}$$
$$\theta_k \geq \theta_i + t_i - M \cdot (1 - o_{ik}) \qquad i, k = 1, \dots, n, i \neq k; \tag{5}$$
$$s_j - r_i - h_i - T \geq M \cdot (x_u - 1) \qquad i = 1, \dots, n; j = 1, \dots, m; u \in U_i \cap U^j; \tag{6}$$
$$s_l - (s_j + b_j) \geq M \cdot (q_{jl} - 1) \qquad j, l = 1, \dots, m, j \neq l; \tag{7}$$

$$d_j - \vartheta_j - v_j \geq 0 \qquad j = 1, \dots, m; \qquad (8)$$
$$\vartheta_j - s_j - b_j \geq 0 \qquad j = 1, \dots, m; \qquad (9)$$
$$\vartheta_l \geq \vartheta_j + v_j - M \cdot (1 - w_{jl}) \qquad j, l = 1, \dots, n, j \neq l; \qquad (10)$$
$$\sum_{e=1}^{n+1} o_{0e} = \sum_{i=0}^{n} o_{i,n+1} = |\tau| \qquad (11)$$
$$\sum_{k=1}^{n+1} p_{0k} = \sum_{i=0}^{n} p_{i,n+1} = |\pi| \qquad (12)$$
$$\sum_{l=1}^{m+1} q_{0l} = \sum_{j=0}^{m} q_{j,m+1} = |\omega| \qquad (13)$$
$$\sum_{l=1}^{m+1} w_{0l} = \sum_{j=0}^{m} w_{j,m+1} = |\varphi| \qquad (14)$$
$$\sum_{k=1}^{n+1} o_{ik} = \sum_{k=0}^{n} o_{ki} = 1 \qquad i = 1, \dots, n; \qquad (15)$$
$$\sum_{k=1}^{n+1} p_{ik} = \sum_{k=0}^{n} p_{ki} = 1 \qquad i = 1, \dots, n; \qquad (16)$$
$$\sum_{l=1}^{m+1} q_{jl} = \sum_{l=0}^{m} q_{lj} = 1 \qquad j = 1, \dots, m; \qquad (17)$$
$$\sum_{l=1}^{m+1} w_{jl} = \sum_{l=0}^{m} w_{lj} = 1 \qquad j = 1, \dots, m; \qquad (18)$$
$$x_u, o_{ie}, p_{ik}, q_{jl}, w_{jl} \in \{0,1\}; r_i, s_j, \theta_i, \vartheta_j \geq 0.$$

The objective function (1) of SSM, z, maximizes the total number of the railcars that can depart, which is equivalent to the minimization of the total dwell time of railcars. Please note that $\sum_{u \in U} \delta_u \cdot \Delta_u$ is a constant and is not explicitly included in the objective function. Constrain set (2) ensures that a hump engine can only start to push an inbound train over the hump after the engine finishes the previous train. Here, M is a big number. Together with constraint (12) and (16) indicate the inspection sequence of inbound trains by the same inspection group. No inbound trains can be humped before it is inspected, which is guaranteed by constraint set (3). Constraint set (4) does not allow starting the inspection of an inbound train before it arrives. Constraint sets (5), (11) and (15) indicate the sequence to inspect inbound trains by the same inspection group, as the inspection group can only inspects the inbound train one by one. Constraint set (6) ensures that there is enough time between the humping and connection of a cut and makes sure that the right-car right train rule. Same to constraint set (7), together with constraint set (13) and (17) ensures that a yard engine can start to assemble an outbound train only after the engine finishes the previous train. Constraint set (8) makes sure that each outbound train meets its scheduled departure time. Constraint set (9) does not allow starting the inspection of an outbound train before it is assembled. Constraint set (10), (14) and (18) indicate the sequence to inspect outbound trains by the same inspection group. Constraint sets (11) to (14) mean the number of inspection group for inbound trains, hump engines, yard engines, and inspection groups for outbound trains respectively.

This model is applicable to a variety of classification yards by have different values of τ, π, ω and φ. In addition the number of engines, the layout and facility capacity of a yard may limit the number of trains that can be humped or assembled simultaneously. For example, only two outbound trains can be assembled simultaneously if there are 2 pullout tracks, even though there are more than 2 yard engines. For those cases, we just need to modify the values of π and ω to represent the number of trains that can be humped or assembled simultaneously.
The planning horizon in rail classification yards is usually one day (24 hours), we test the model by using CPLEX under different scenarios on a PC with an I5 CPU and 4 GB RAM (Table 1). For all of those scenarios, the planning horizon is 24 hours, the inspection times of inbound

trains and outbound trains are both 57.6 minutes, hump time is 2.45 car per minute, and the average assemble time is set at 25 minutes. CPLEX can yield an optimal schedule within an acceptable amount of run time for most of the scenarios. When the inspection times of inbound trains and outbound trains are 60 minutes, it is impossible to inspect all the trains with only one inspection group during the planning horizon. Numerical experiments with various scenarios and different numbers of hump engines and yard engines are conducted to verify the model and investigate the impact of increased capacity on the yard performance measured by the total dwell time. The numerical results show that the hump capacity and assembly capacity should be balanced in order to have a smooth and efficient classification yard operation. A case study based on a U.S. Class I railroad's historical data shows that the proposed method can help to decrease the total unconnected railcars and therefore the total dwell time compared with the current practice of static sequencing. Furthermore, dynamic sequencing can reduce total dwell time compared to static sequencing, especially when more trains are classified at a yard. Numerical experiments demonstrate that the saving of average dwell time with dynamic sequencing in Figure 5. However, the savings on average dwell time for each railcar become smaller when the traffic volume goes up. Once the volume through a yard is close to its capacity, the dwell time per rail car goes up very quickly as shown in Figure 5 and the benefit of dynamic sequencing diminishes. The research team also built simulation models for various yard configurations and the simulation results show a typical relationship between dwell times and yard traffic volumes (measured by the number of cars per day) in Figure 5.

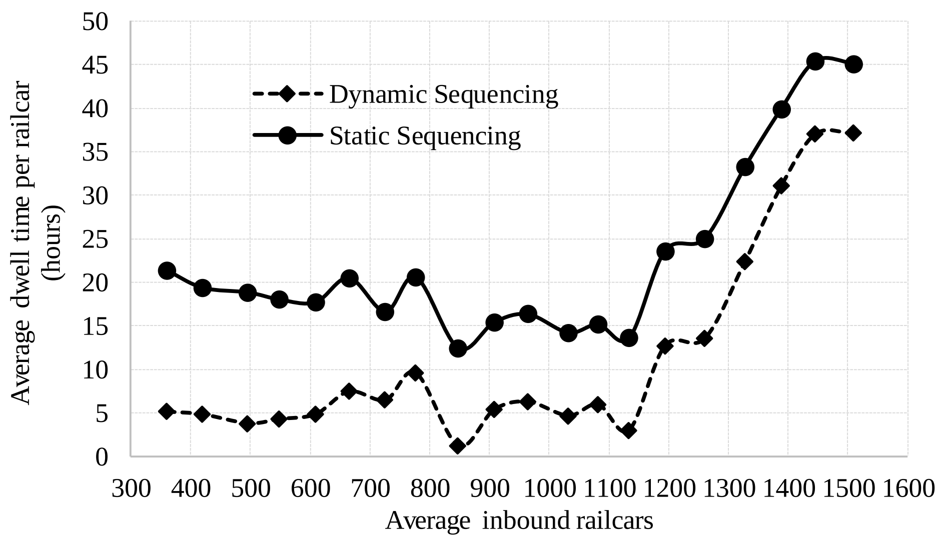

Figure 5. Average dwell time per railcar between the two sequencings with different inbound railcars

We built a generic simulation model and tested various configuration. Table 1 is one configuration example.

Table 1: Input Parameters for One Simulation Configuration

Parameters	Unit of Measure	Value
Arrival Rate	Train/hour	0.7
Size	Number of Cars/Train	(**int**) triangular(70,90,120)
Hump Engine	Count	2
Pullback Engine	Count	2
Humping Speed	Car/minute	3
Assemble Speed	Car/minute	1
Inspection Time of Inbound and outbound	Car/minute	3
Simulation Model Time	days	30

We conducted 30 simulation runs with this example model, Table 2 summarizes the simulation results. The minimum cars per day is 1,344, and the min time in system is 9.59 hours. The average time in system (Dwell Time) is 24.86 hours. And the average cars per day is 1,580.32.

Table 2: Summary of Simulation Results

TIS:		Cars:	
Count	30	Count	30
Min	9.59	Min	1,344
Deviation	19.741	Deviation	143.569
Sum	745.878	Sum	47,409.60
Mean	24.86	Mean	1580.32

Figure 6 shows the relationship between dwell time and daily value and indicates that the capacity of this yard is about 1,700 cars per day. When the cars per day through a yard is lower than its capacity, the increase of the car volume will not significantly influence the total dwell time, as shown in this figure. However, when the car volume reaches the yard capacity, the dwell time for railcars increases very quickly so that very soon no more cars can be contained in the yard.

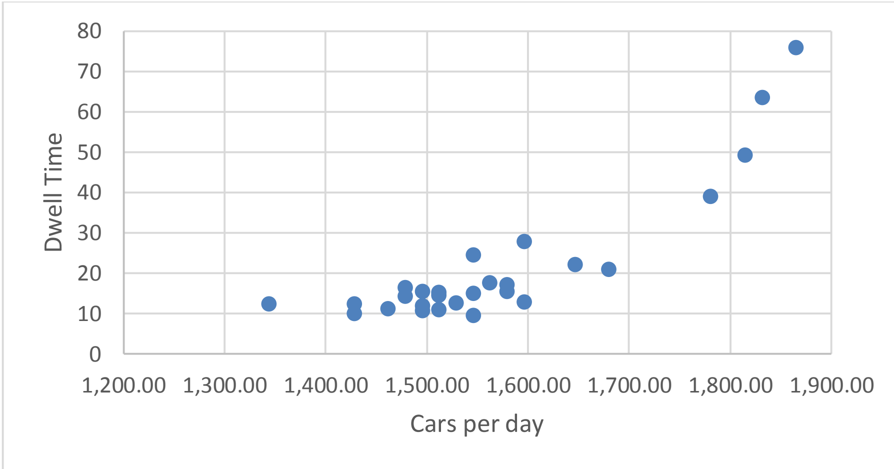

Figure 6: Dwell Time vs Cars per day

We fit an analytical model for the relation between the dwell time and cars volume from the simulation results. Many different types of dwell time and volume functions have been proposed and used in practice in the past, for a review article see (Branston 1976). By far the most widely used dwell time and volume functions are the BPR functions (Roads 1964). However, the basic BPR function was used for highway transportation, later Fernandez et al. (2004) used the following BPR type function (19), which is a power function.

$$D_i = a + b(\frac{V_i}{CAP_i})^c \tag{19}$$

Here, D_i is the average dwell time, V_i is the daily volume (measured by railcars), and CAP_i is the capacity of yard i. a, b, and c are parameters to fit based on simulation results. This project yields empirical models to describe the relationship between traffic volume and dwell time based on a power function for each yard. For a specific yard i that was simulated before, we can have the relationship of

$$D_i = 12.2546 + 9.5274(\frac{V_i}{1663.2})^{16.59}. \tag{20}$$

The model fits the simulation results very well, as shown by Figure 7 and the capacity of the yard is 1,663. The analysis of variance shows a P_value<0.0001 and verify the model.

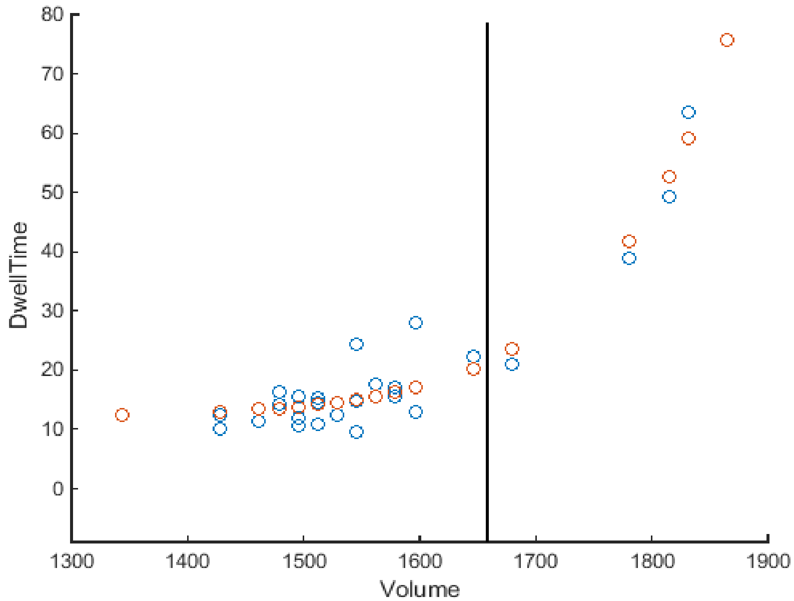

Figure 7: Compare simulation and analytical results

Further statistical analysis shows that a yard capacity is mainly decided by the number of yard engines, the classification track lengths, and the yard configuration (single-ended vs. double-ended) have large impacts on the capacity of yards. With the above experimental results, we now can determine the theoretical capacity for each yard by using our developed simulation model. We find the following seven yard data from public sources, summarized in Table 3, to verify our method.

Table 3: classification yard practical operational data

	Number of Receiving Tracks	Number of Classification Tracks	Number of Departure Tracks	Average Dwell Time (Hours)	Calculated Capacity
Bailey Yard_UP	17	114	16	28.75	2900
Roseville Yard_UP	8	55	8	31.05	1750
Barstow Yard_BNSF	10	48	10	41.4	1800
Galesburg Yard_BNSF	5	40	5	39.77	1500
Northtown Yard_BNSF	12	63	9	34.28	1900
Conway Yard(Eastbound)_NS	10	54	10	31.88	1750
Enola Yard(Westbound)_NS	16	58	16	24.45	1550

Then we use our simulation and analytical model to calculate the average dwell time for each yard and compare them against the reported average dwell times

Table 4: Comparison of simulation, analytical and actual dwell times (Hours)

Average Simulated Daily Volume (Cars)	Simulation Dwell Time	Analytical Dwell Time	Practical Dwell Time
2993.76	29.95	31.97216	28.75
1805.76	31.474	32.15636	31.05
1900.8	40.759	39.61227	41.4
1639.44	40.756	39.84252	39.77
2019.6	33.929	34.56197	34.28
1805.76	32.547	29.45636	31.88
1663.2	24.209	26.38576	24.45

We calculate the R-square for simulation and analytical model related to the practical value. The simulation has R^2 =0.98, while the analytical capacity model has R^2 = 0.89. Both have a very good prediction accuracy.

4. Conclusions

This study uses optimization, simulation, and statistical analysis to systematically analyze the capacity at railway classification yards. Better planning based on optimization techniques can help to increase yard capacity. Numerical results show that the hump capacity and assemble capacity should be balanced in order to have a smooth and efficiency classification yard operation. A macro-level model describing yard capacity can help the network capacity analysis so that railroads can identify the improvement opportunities in a systematic way. Furthermore, the model may help to provide quick responses to any disruption to the network. The research efforts are the first few that considers both how to use optimization in sequence, scheduling, and connection to improve railway classification yards at the micro-level and how to model the yard capacity based on yard features at the macro-level. Implementing those models in the real-worlds needs supports from major railroads. Several publications have been out of this funded research and the macro-level model will be further promoted by the research team. The team will also further pursue collaboration from railroads to calibrate the capacity models and persuade them to adopt the models for their network analysis.

Publications out of This Project

H. Li, M. Jin, and S. He "Sequencing and Scheduling in Railway Classification Yards," *Transportation Research Record, Journal of Transportation Research Board*, Volume 2475, pp. 72-80, 2015.

H. Li, M. Jin, R. Song, S. He, and J. Song, "Dynamic Railcar Connection Planning in Classification Yards," Accepted by *Transportation Letters, The International Journal of Transportation Research*, 2015, http://dx.doi.org/10.1179/1942787515Y.0000000010.

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