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Macro-Level Classification Yard Capacity Modeling

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To the Graduate Council:

I am submitting herewith a thesis written by Licheng Zhang entitled "Macro-Level Classification Yard Capacity Modeling." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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ABSTRACT

Classification yards play a very significant role in railroad freight transportation and are often regarded as bottlenecks for railroad networks. In order to understand the capacity of a railroad network, it is important to model the volume-dwell time relationship at classification yards. The dwell time at a yard is related to the yard volume and yard capacity. When the volume is over the yard capacity, the dwell time will increase sharply. Based on a generic yard simulation model, this study fits the widely used Bureau of Public Roads function used in highway capacity to represent the dwell time and volume relationship. This study develops a yard capacity model that incorporates major yard features, such as the humping speed, the number of humps, the number of classification tracks and the number of pullback engines. The model is validated by historical data from 15 classification yards.

With the developed model in this thesis, it would help decision maker understand and make use of the capacity of existing yard infrastructure, also it could be used to justify capital investment in the yard operation. For example, it can help yard workers estimate the present yard capacity based on these yard features. With this estimated yard capacity and cars volume, then yard workers can predict the future dwell time. If the estimated yard capacity is lower than the cars volume, and the dwell time is very large, then it may be necessary to expand the present yard infrastructure. Once the yard capacity can satisfy the demand of railroad freight transport, it could reduce the dwell time very much, which is sure to benefit the whole railway network.

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CHAPTER ONE
INTRODUCTION AND GENERAL INFORMATION

Railroad transportation is a very important transportation mode. It has some irreplaceable advantages compared to other transportation modes. Its transport capacity is large; it has high speed over long distances; and it is cheap. All of these reasons make railroad transportation become more and more popular in freight movement. Total U.S. railroad freight ton-miles have doubled and density (measured by total ton-miles per mile of track) tripled between1980 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 increasing concern about environmental issues makes the future demand for railroad transportation very likely to increase. Railroad transportation is considered an environment friendly freight transportation mode. According to an independent study by the Federal Railroad Administration, railroad transportation is about four times more fuel efficient than trucks. Railroad transport is useful to alleviate the highway gridlock, decrease the greenhouse gas emissions, and reduce the pollution according to the 2015 reports from Association of American Railroads (Railroads 2015). Figure 1.1 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. However, present railway infrastructure cannot satisfy these increasing demand. There are two ways to tackle this issue. One is to increase present railway infrastructure capacity and the other is to improve the operational efficiency of present infrastructure.

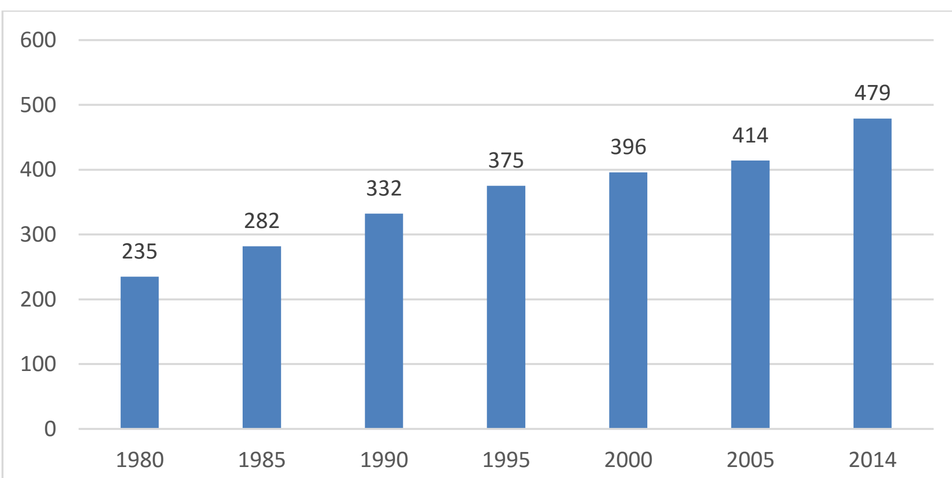

Figure 1.1. Freight rail fuel efficiency (ton miles per gallon)

This thesis will focus on the study of classification yard capacity modelling. Classification yards play a key role in railroad freight transportation and have the most complex operation in the rail transportation industry. For example, one of the problems in classification yard is called block-to-track assignment, which is an NP-hard problem (Jacob et al. 2011).

A rail freight train consists of dozens rail cars hauled by locomotives on a railway. A classification yard is used to split and regroup rail cars according to their destinations. Humping and assembling are two main processes in classification yard operations. They basically break up and reconfigure trains. Yard operations also require various resources, such as locomotives, dispatchers, hump engines and pullback engines.

Hump yards are the largest and most effective classification yards. They have a hump (or two humps), which consists of a lead track on a small hill and a hump engine. The hump engine pushes rail cars to the hump and lets gravity to move rail cars to their destination classification tracks. A typical hump yard layout is like Figure 1.2, which includes 3 major parts: receiving area, classification area and departure area.

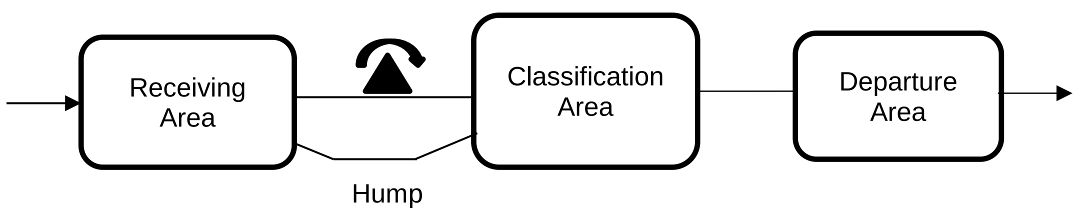

Figure 1.2. Layout of a typical classification yard

Rail cars pass through the yard according to the following processes. First, the inbound train enters the receiving area where locomotives are detached from rail cars. Second, rail cars are inspected for mechanical problems. If the condition is good, they'll be sent to hump. While humping, these rail cars are rearranged and sorted on different tracks in the classification area. Another engines (called yard engine or pullback engines) pulls sorted cars to their designated departure track. Rail cars are then assembled to their respective outbound trains according to a departure schedule. Finally, the outbound train leaves the yard from the departure area after inspection.

A rail car spends about two thirds of its system time within yard, and the significant portion of these time in classification yard is spent in waiting for humping and assembling (Crane et al. 1955). Obviously, the long dwell time of rail cars in the yard is a big barrier for the improvement of railroad transportation

efficiency. Therefore, it is necessary to study how to reduce the dwell time and improve the rail yard operational performance. Dwell time is the time that a rail car stays at a yard and is usually expressed in hour. 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 rail car volume, the number of tracks, humping speed and various yard operational policies. Rail car volume is the number of rail cars through the yard per day. The number of rail tracks is one of the most fundamental infrastructure of classification yard, and it was determined in the yard planning stage. Once a yard was constructed, it cannot be changed easily. Therefore, we need to design the best number of tracks before 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. The number of tracks and humping speed belongs to yard features, they are strongly related to yard capacity. The yard capacity is measured by the maximum number of rail cars that can be handled per day in the yard without significantly increasing average dwell time. In a word, the reason why rail cars have such a long dwell time is the yard capacity couldn’t satisfy the high volume of rail cars. Therefore, in order to reduce dwell time, it’s necessary to study how the capacity is determined, and how it affects dwell time. Reducing the dwell time, will largely improve yard productivity and efficiency and benefit the whole rail network.

CHAPTER TWO
LITERATURE REVIEW

Macro-level yard capacity models could be developed and used from the strategic or tactical view to analyze the yard operations. Some sample decisions that yard capacity models can help to answer are:

- Should we add more classification tracks into the present yard infrastructure?
- Should we add one more pullback engine?
- Should we build a new hump area?

Early macro-level railway transportation models either did not consider the details of yard operations or assumed that it is a linear model related to its dwell time. For example, (Sayarshad and Ghoseiri 2009, Sayarshad and Tavakkoli-Moghaddam 2010) proposed a model to capture the railway network information such as yard capacity, unmet demands, and number of loaded and empty rail cars at any given time and location. They defined yard capacity as the ability to receive, process, and dispatch the rail cars. However, they assumed a fixed number of rail cars in the yard, which is not necessary true in practice. (Fernández L et al. 2004) provided a strategic model for freight rail transportation. In their paper, they considered some of the yard capacity constraints, such as the availability of engines, and modeled the yard capacity with the classical BPR type function, which will be discussed in more detail in the following section. However, early research on rail yard capacity analysis only considered the yard as a node for the railway network and did not pay much attention on the details of yard operations. As mentioned before, classification yards are bottlenecks for the whole railway network operations.

In addition, among these researches on the specific yard capacity analysis, they usually assumed it is a linear relationship between dwell time and rail car volume or did not capture the relationship between dwell time and volume at all. For instance, (Thomet 1971) and (Assad 1980) proposed a model to capture the rail cars dwell time by modeling it as a linear function to the number of rail cars carried by a train. This relationship is shown in Equation 2-1. The dwell time function at a given yard j for train i is:

Equation 2-1:

$$W_j + v_j x_{ij}$$

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 rail cars carried by train i when entering yard j. Figure 2.1 illustrates this model, which has a fixed dwell time W_j at yard j. When the number of rail cars increases, the dwell time of a train will increase linearly.

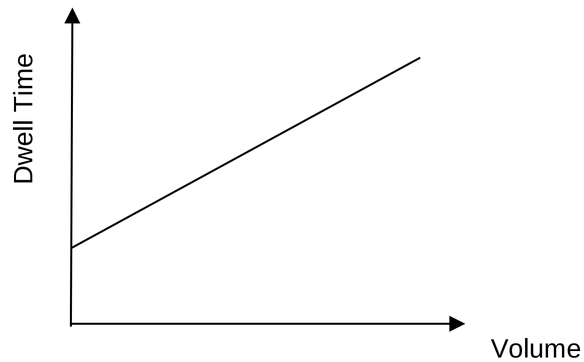

Figure 2.1. A linear model for yard capacity

This simple model fails to capture the relationship of yard features on the dwell time. In practice, the dwell time at a yard depends on the yard features and operational conditions, such as timetables of inbound and outbound trains, humping sequence, and block-to-track assignment. From the results of Petersen's research (Petersen 1977), the yard capacity model should show the relationship between the average dwell time for rail cars vs. the volume through a yard as Figure 2.2. As we can see, the dwell time almost keeps constant when the volume is not big enough, but when the volume passes some threshold value, the dwell time increases sharply. We will define this threshold value as the yard capacity, which will be stated in more detail in the next section.

We call the model that captures the relationship between the yard dwell time and the yard volume, as illustrated in Figure 2.2, macro-level yard capacity model. With this model, it will be helpful to estimate the yard capacity, and be used to make some strategic and tactical decisions.

In literature, numerous approaches have been developed to model the yard capacity. All of these methods can be classified in three levels: Analytical Methods, Optimization Methods, and Simulation Methods, based on the research survey from (Abril et al. 2008, Gatto et al. 2009).

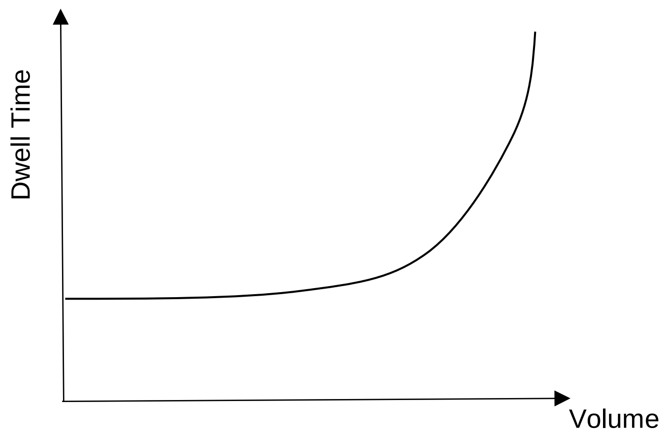

Figure 2.2. A typical yard dwell time and volume relationship

2.1 Analytical Methods

The first yard capacity analytical model came from Petersen’s two sequential papers (Petersen 1974, Petersen 1975). In his papers, he built two queues in the classification yard. One is the waiting of rail cars for humping; and the other is the waiting queue for pullback. He assumed that trains arrive the yard according to a Poisson process and modeled the yard queuing systems with the whole train as the unit. These models are mainly used to predict the dwell time over a single train line and a partially double track line. (English 1977) refined Petersen’s approach and developed dwell time expressions in greater detail. These models were verified by two classification yards owned by the CN railroad. They used Petersen’s model to estimate the dwell time and compare the dwell time distribution with the actual dwell time distribution, the results showed they have the similar shape. This suggests that the assumption of queuing models worked very well. However, (Turnquist and Daskin 1982) suggested it would be more clear and convenient to use individual rail car rather than the whole train as arrival units . Therefore, they considered a batch arrival queuing model 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 showed that the Poisson arrival assumption for train arrivals is reasonable. However, both studies did not consider the impact of the yard traffic volume on the dwell time.

The above analytical models based on the queuing theory are not widely used in actual rail yard operations because they depend on many assumptions and are too complicated for practitioners.

2.2 Optimization Methods

Optimization models for the analysis of rail yard capacity mainly focus on obtaining the optimal scheduling timetables. Researchers used some of mathematical programming methods, such as mixed integer programming and heuristic algorithms to obtain the optimal scheduling timetables. (Szpigel 1972) is the first to apply the branch and bound method for scheduling timetables given the outbound train timetables. He considered the outbound trains depart the yard with disjunctive constraints, and solved it by branch and bound methods. Specifically, he calculated bounds by the relaxation of disjunctive constraints. (Crainic et al. 1984) described a general optimization model which takes into account the interactions between train scheduling and classification work allocating, but they considered the dwell time fixed. (Crainic et al. 1990) developed a multimode network optimization model, and implemented it in an interactive graphic system, which offered an efficient framework for railroad transportation strategic planning. A useful survey of discrete optimization in railway scheduling, including the topic of periodic event scheduling problems, can be found in (Bussieck et al. 1997). (Cordeau et al. 1998) reviewed some frequently-used optimization models on railroad transportation problems. (Oliveira and Smith 2000) modeled the problem of assignment-to-track as a special case of the Job–Shop Scheduling Problem. They considered inbound trains as jobs to be scheduled on tracks which are regarded as resources. They designed a hybrid algorithm under the constraint programming paradigm and showed its application in practical applications. (Shi and Zhou 2015) provided a mixed integer programming model for optimizing multi-level operations process in railroad yards, but they didn’t consider some very important practical operational constraints in their models. In practice, some of railroads companies began to combine these optimization methods into their decision support systems (Barnhart et al. 2000, Ahuja et al. 2007, Jha et al. 2008, D’Ariano and Pranzo 2009). However, they didn’t consider the yard capacity as a whole, but only considered track capacities. (Jha et al. 2008, Hauser and Maue 2010) designed heuristic optimization methods for solving the block to track assignment problem, they assumed the yard capacity with a fixed value but did not study how to determine the yard capacity, which compared to integer programming has shorter computational time. (Li et al. 2014) used a heuristic algorithm based on the harmony search strategy to solve the pullout allocation problem, their results also displayed the advantage of computational time. (Javadian et al. 2011) used network optimization methods to determine what the optimal capacity of each

yard, but the results are not very accurate, because it didn't consider the impact of the yard features on capacity.

Optimization methods have some disadvantages, for instance, they are very complicated, and they do not have the flexibility to incorporate operational condition changes.

2.3 Simulation Methods

To avoid some of shortcomings of analytical and optimization models, computer simulation has been used in several recent studies. The application of simulation on classification yards mainly focuses on two parts. One is for layout planning and the other is for yard operations. For example, (Abacoumkin and Ballis 2004) designed a computer simulation system for yard layout planning. (Petering 2009) applied simulation to test the effect of block width and storage yard layout on marine container yard performance, which gave them much flexibility to design yard configurations. For the operation side, (Ferreira and Sigut 1995) developed a computer simulation model to evaluate operating strategies and performance. (Marinov and Viegas 2009) built a simulation model of flat yards with the simulation package SIMUL. (Lin and Cheng 2011) from Norfolk Southern developed a simulation model of classification yards, which incorporated some difficulties in the yard simulation, such as re-humps. Their simulation models also considered inbound and outbound trains schedule, rail car assignment plans, resource utilization, track utilization percentage, and dwell time. Based on their simulation results, the pullback process is a bottleneck in the yard operations. Which is also concluded by (Dirnberger and Barkan 2007). CSX, another big railroad company, also developed their own computer simulation systems for yard design and operations (Dick and Dirnberger 2014). They called the simulation system HYSS, from their practice, this simulation system is very efficient to evaluate the yard performance.

Simulation models are very flexible. It is easy to change various parameters and yard features in order to represent different yards conditions. It is very convenient to do scenario analysis by changing parameters in simulation models. However, developing a detailed yard simulation model is time consuming. Furthermore, it is hard to incorporate simulation models developed for individual yards into network capacity analysis. The improvement suggestions from individual yard simulation model may not benefit the overall network efficiency.

In conclusion, a single method (e.g., analytical mode, optimization, or simulation) may not be suitable for the macro-level yard capacity analysis. Therefore, it's a trend to develop tools with integrated methods that embed two or more of the

above methods. For example, (Márton et al. 2009) combined an integer programming approach and simulation models to successfully develop and verify an improved classification schedule for a real world train classification instance. (Jacob et al. 2011) provided a multistage method for freight train classification. The goal of this thesis is to develop a macro-level yard capacity model with the integration of simulation and analytical methods. The model will capture the relationship between rail car dwell time and traffic volume and incorporate the yard physical features and operational conditions. The model is also expected to facilitate rail network capacity analysis.

CHAPTER THREE
SIMULATION MODEL FOR YARD CAPACITY ANALYSIS

In this section, a simulation model is developed to mimic yard operations. The simulation results will help to build an analytical model that captures the relationship between dwell time and traffic volume. The reason why simulation is selected as the prerequisite of analytical model partly because simulation experiments could generate enough data, which is essential to build analytical models. This simulation model will use rail cars as the simulation object and assume that cars arrive at the rail yard in batches. This simulation model is consist of the following six processes:

1) Generating Inbound Train

Inbound trains are those that come into a yard from other yards. For each inbound train, it is consist of a group of different rail cars and these rail cars are grouped in different blocks. A block is a set of rail cars with the same destination. 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 the 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 number of rail cars in each train 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 rail car number is x, maximum is y, and the mode 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}.
During the receiving area, the inbound train locomotives are detached from the rail cars, and these yard crews will inspect the operational condition and mechanical problems for these rail cars. Let the inspection time is t minutes for each car. As mentioned in literature review, inspection is not a bottleneck.
In the 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 n.

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. 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 outbound time is after the second train. Then it may be better to hump the second inbound train which arrives later but carries rail cars with an earlier outbound train schedule.

In order to reduce the dwell time in the yard, it's essential to specify a humping sequence that ensures the outbound trains depart from the yard on schedule. In our simulation model, we use First-In First-Out (FIFO) method to assign the hump sequence, which is widely used in the 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. We assume the humping rate is μ cars per hour.

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 handle the block-to-track assignment. From left to right, we assign index to these classification tracks 1 to N. 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 it 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 set several blocks of cars 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 3.1 (RAS). If so, those rail cars

may need to be re-humped later when some of other classification tracks become available again. However, we won't consider re-hump in our simulation model.

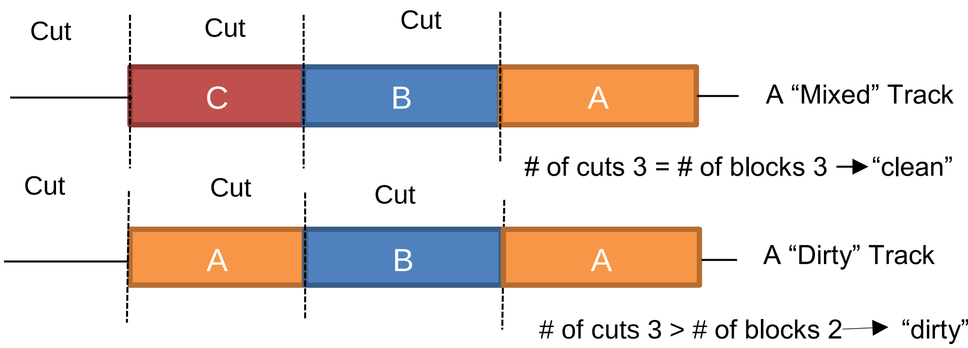

Figure 3.1. Cut, block, clean and dirty track definition

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 be assembled to which outbound trains? Second, which lines of rail cars at the classification track should be pulled by the pullout engine? For the first question, it is mainly determined by the departure schedule of these blocks of rail cars. In practice, the outbound schedule would be specified in the rail yard operational plan. 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. At the time of generating a block, we randomly assign an outbound train for it. 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.

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. In the case of 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 practice, it can also happen that an outbound train with scheduled time may be delayed to depart. It is usually caused by some 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 respective schedule.

The above six processes are summarized in Figure 3.2.

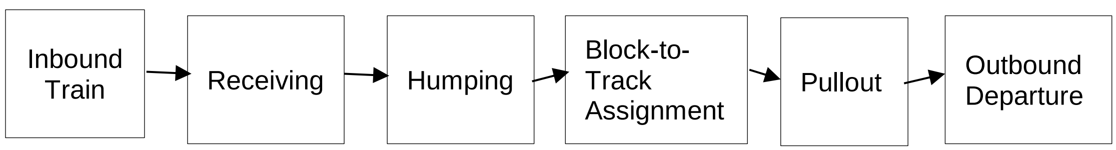

Figure 3.2. Processes of classification yard simulation

3.1 Data Collection

In order to build the simulation model, we first need to collect infrastructure data and operational data from classification yards. Here, we got data from the following yards: Birmingham Yard, Knoxville Yard, Bailey Yard, J.R. Davis Yard, Barstow Yard, Galesburg Yard, Northtown Yard, Conway Yard, Enola Yard, Argentine yard, Avon yard, Cumberland Yard, and Selkirk Yard, Linwood Yard, Radnor Yard, West Colton Yard. Among them, some of yards are consist of two parts: westbound yard and eastbound yard. The following provides details about these collected data for various yards.

1. Birmingham Yard

The Birmingham Yard is located in Birmingham, Alabama. It is operated by Norfolk Southern corporation. The data for Birmingham Yard as follows, most of these data were obtained by communicating with Norfolk Southern employees.

a. Yard Infrastructure
    - Receiving area: 12 receiving tracks
    - Classification area: 56 classification tracks
    - Departure area: 12 departure tracks
    - One hump

b. Resources
    - One hump engine: means only one hump job at a time
    - Two pullback engines: means two concurrent pullback jobs

c. Operational Parameters
    - Maximum humping rate: 2 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 1700 cars
    - Daily Dwell Time: Around 28.9 hours

2. Knoxville Yard

The Knoxville Yard is also called John Sevier Yard which is located in Knoxville, Tennessee, and it is also operated by Norfolk Southern Corporation. We got the following data mainly by field research. We visited this yard last December, and interviewed their yard manager.

a. Yard Infrastructure
    - Receiving area: 12 receiving tracks
    - Classification area: 48 classification tracks
    - Departure area: 10 departure tracks
    - One hump
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 3 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 1550 cars
    - Daily Dwell Time: Around 35.9 hours

3. Bailey Yard

The Bailey Yard is operated by Union Pacific, and it is located in North Platte, Nebraska. Bailey Yard is one of the most important components of Union Pacific's rail network. We find its information from the Union Pacific website (UP).

a. Yard Infrastructure
    - Receiving area: 17 receiving tracks
    - Classification area: 114 classification tracks
    - Departure area: 16 departure tracks
    - One hump
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - One pullback engine: means only one pullback job at a time
c. Operational Parameters
    - Maximum humping rate: 4 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 4500 cars
    - Daily Dwell Time: Around 43.5 hours

4. J.R. Davis Yard

The J.R. Davis Yard is also called Roseville Yard, located in northeast of Sacramento, California. It is also operated by Union Pacific, and is the largest rail facility on the West Coast. We find its information from the Union Pacific website (UP).

a. Yard Infrastructure
    - Receiving area: 8 receiving tracks
    - Classification area: 55 classification tracks
    - Departure area: 8 departure tracks
    - One hump
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 3 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 2200 cars
    - Daily Dwell Time: Around 30.4 hours

5. Barstow Yard

The Barstow Yard belongs to BNSF. It is located in Southern California, which is a major hub for transportation. Most BNSF trains originate or terminate at Barstow Yard. We find its information from the University of Southern California railyards website (USC).

a. Yard Infrastructure
    - Receiving area: 10 receiving tracks
    - Classification area: 48 classification tracks
    - Departure area: 10 departure tracks
    - Two humps
b. Resources
    - Two hump engine: means only one hump job at a time
    - One pullback engine: means only one pullback job at a time
c. Operational Parameters
    - Maximum humping rate: 3 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 2200 cars
    - Daily Dwell Time: Around 37.6 hours

6. Galesburg Yard

Galesburg Yard is located three miles southwest of the center of Galesburg, Illinois. It is also operated by BNSF. We find its information from the University of Southern California railyards website (USC).

a. Yard Infrastructure

- Receiving area: 17 receiving tracks
- Classification area: 62 classification tracks
- Departure area: 17 departure tracks
- One hump

b. Resources
   - Two hump engines: means two concurrent hump jobs
   - One pullback engine: means only one pullback job at a time

c. Operational Parameters
   - Maximum humping rate: 3 cars/min

d. Historical Volume and Dwell Time
   - Daily Volume: Averagely 2600 cars
   - Daily Dwell Time: Around 29.8 hours

7. Northtown Yard

The Northtown Yard was built on the site of the old Northern Pacific yard in Minneapolis, Minnesota. BNSF built this yard between 1971 and 1976. We find its information from Don Winter website (Donwinter).

a. Yard Infrastructure
   - Receiving area: 12 receiving tracks
   - Classification area: 47 classification tracks
   - Departure area: 9 departure tracks
   - One hump

b. Resources
   - One hump engine: means only one hump job at a time
   - One pullback engine: means only one pullback job at a time

c. Operational Parameters
   - Maximum humping rate: 2.5 cars/min

d. Historical Volume and Dwell Time
   - Daily Volume: Averagely 1350 cars
   - Daily Dwell Time: Around 23.8 hours

8. Conway Yard

The Conway Yard is 23 miles northwest of Pittsburgh, Pennsylvania. It is one of the largest railyards in the eastern United States, and is owned by Norfolk Southern. It is consist of two parts: eastbound yard and westbound yard. We find its information from the University of Southern California railyards website (USC).

Eastbound Yard:

a. Yard Infrastructure
   - Receiving area: 10 receiving tracks
   - Classification area: 54 classification tracks
   - Departure area: 10 departure tracks
   - Two humps

b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 3 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 3000 cars
    - Daily Dwell Time: Around 27.3 hours

Westbound Yard:

a. Yard Infrastructure
    - Receiving area: 11 receiving tracks
    - Classification area: 53 classification tracks
    - Departure area: 10 departure tracks
    - Two humps
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 4 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 3000 cars
    - Daily Dwell Time: Around 28.1 hours

9. Cumberland Yard

The Cumberland Yard is located in the Cumberland, Maryland. It is owned and operated by CSX Transportation. It is 3.5 miles long and occupies 95 acres. We got its related data from Wikipedia (Wikipedia).

a. Yard Infrastructure
    - Receiving area: 8 receiving tracks
    - Classification area: 33 classification tracks
    - Departure area: 8 departure tracks
    - One hump
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 4 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 1300 cars
    - Daily Dwell Time: Around 29.5 hours

10. Argentine Yard

The Argentine Yard is located on the southern part of Wyancotte County, which is a neighborhood in Kansas City, Kansas. It was built in the 1950's as a dual hump yard with eastbound and westbound classification yards. It is one of the largest classification yards owned by BNSF. We got its data from the University of Southern California railyards website (USC).

Eastbound Yard:

a. Yard Infrastructure
    - Receiving area: 23 receiving tracks
    - Classification area: 48 classification tracks
    - Departure area: 14 departure tracks
    - One hump
b. Resources
    - One hump engine: means only one hump job at a time
    - One pullback engine: means only one pullback job at a time
c. Operational Parameters
    - Maximum humping rate: 2 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 3000 cars
    - Daily Dwell Time: Around 27.3 hours

Westbound Yard:

a. Yard Infrastructure
    - Receiving area: 16 receiving tracks
    - Classification area: 53 classification tracks
    - Departure area: 14 departure tracks
    - One hump
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 4 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 2800 cars
    - Daily Dwell Time: Around 38.7 hours

11. West Colton Yard

The West Colton Yard is located in the Bloomington, California. It was officially opened on February 23, 1973 by Union Pacific. It is 6 miles long. We got its related data from Carrtrack website (Carrtracks).

a. Yard Infrastructure
    - Receiving area: 9 receiving tracks

- Classification area: 48 classification tracks
- Departure area: 12 departure tracks
- One hump

b. Resources
  - One hump engine: means only one hump job at a time
  - One pullback engine: means only one pullback job at a time

c. Operational Parameters
  - Maximum humping rate: 2 cars/min

d. Historical Volume and Dwell Time
  - Daily Volume: Averagely 1200 cars
  - Daily Dwell Time: Around 20.9 hours

12. Enola Yard

The Enola Yard is located East Pennsboro Township, Pennsylvania. It was built in 1905 with two classification yards: eastbound and westbound classification yards. It is owned by Norfolk Southern Railway. We got its data from Wikipedia (Wikipedia).

Westbound Yard:

a. Yard Infrastructure
  - Receiving area: 20 receiving tracks
  - Classification area: 25 classification tracks
  - Departure area: 20 departure tracks
  - One hump

b. Resources
  - One hump engine: means only one hump job at a time
  - Two pullback engines: means two concurrent pullback job

c. Operational Parameters
  - Maximum humping rate: 2.5 cars/min

d. Historical Volume and Dwell Time
  - Daily Volume: Averagely 900 cars
  - Daily Dwell Time: Around 24.5 hours

Eastbound Yard:

a. Yard Infrastructure
  - Receiving area: 21 receiving tracks
  - Classification area: 17 classification tracks
  - Departure area: 20 departure tracks
  - One hump

b. Resources
  - One hump engine: means only one hump job at a time
  - Two pullback engines: means two concurrent pullback jobs

c. Operational Parameters
  - Maximum humping rate: 3 cars/min

d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 800 cars
    - Daily Dwell Time: Around 27.6 hours

13. Selkirk Yard

The Selkirk Yard is located in Selkirk, New York, which is about 8 miles south of Albany. It is owned and operated by CSX Transportation, and it's a major classification yard for the northeast United States. We got its related data from Wikipedia (Wikipedia).

a. Yard Infrastructure
    - Receiving area: 11 receiving tracks
    - Classification area: 70 classification tracks
    - Departure area: 9 departure tracks
    - Two humps

b. Resources
    - Two hump engines: means two concurrent hump jobs
    - Two pullback engines: means two concurrent pullback jobs

c. Operational Parameters
    - Maximum humping rate: 3 cars/min

d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 3000 cars
    - Daily Dwell Time: Around 33.5 hours

14. Radnor Yard

The Radnor Yard is four miles south of downtown Nashville, Tennessee. It is owned and operated by CSX Transportation. We got its related data from Wikipedia (Donwinter).

a. Yard Infrastructure
    - Receiving area: 13 receiving tracks
    - Classification area: 56 classification tracks
    - Departure area: 10 departure tracks
    - Two humps

b. Resources
    - Two hump engines: means two concurrent pullback jobs
    - One pullback engine: means only one pullback job at a time

c. Operational Parameters
    - Maximum humping rate: 3 cars/min

d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 2200 cars
    - Daily Dwell Time: Around 27.3 hours

15. Linwood Yard

The Linwood Yard is one of the largest classification yards in North Carolina. It is operated by Norfolk Southern Railway and it is located 3 miles north of Salisbury off Interstate 85 in Davidson County, west of Linwood. We got its related data from Wikipedia (Wikipedia).

a. Yard Infrastructure
    - Receiving area: 12 receiving tracks
    - Classification area: 60 classification tracks
    - Departure area: 8 departure tracks
    - One hump
b. Resources
    - One hump engine: means only one hump job at a time
    - Two pullback engines: means two concurrent pullback jobs
c. Operational Parameters
    - Maximum humping rate: 2 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 2200 cars
    - Daily Dwell Time: Around 25.6 hours

16. Avon Yard

The Avon Yard is located in Indianapolis, Indiana. It is owned and operated by CSX Transportation, and it’s a major classification yard for the northeast United States. We got its related data from the University of Southern California railyards website (USC).

a. Yard Infrastructure
    - Receiving area: 10 receiving tracks
    - Classification area: 55 classification tracks
    - Departure area: 12 departure tracks
    - Two humps
b. Resources
    - Two hump engines: means two concurrent hump jobs
    - One pullback engine: means only one pullback job at a time
c. Operational Parameters
    - Maximum humping rate: 3 cars/min
d. Historical Volume and Dwell Time
    - Daily Volume: Averagely 1800 cars
    - Daily Dwell Time: Around 22.4 hours

These are the total 16 classification yards. I summarize it in Table 3.1. The dwell time is from Railroad Performance Measures website (RPM). The analysis will be based on the average dwell time in January, 2016. In addition, some other operational data are necessary in order to build this simulation model. These parameters are usually similar for each yard, such as the track capacity, which is

Table 3.1. Summary of yard information

	RT	CT	DT	Hump Nums	Hump Speed	Hump Eng	Pull Eng	Vol	DT
Bailey Yard	17	114	16	1	4	2	1	4500	43.5
J.R. Davis	8	55	8	1	3	2	2	2200	30.4
Barstow Yard	10	48	10	2	3	2	1	2200	37.6
Galesburg Yard	17	62	17	1	3	2	1	2600	29.8
Northtown Yard	12	47	9	1	2.5	1	1	1350	23.8
Conway East Yard	10	54	10	2	3	2	2	3000	27.3
Conway West Yard	11	53	10	2	4	2	2	3000	28.1
Cumberland Yard	8	33	8	1	4	2	2	1300	29.5
Argentine East Yard	23	48	14	1	2	1	1	1200	21.2
Argentine West Yard	16	53	14	1	4	2	2	2800	38.7
West Colton Yard	9	48	12	1	2	1	1	1200	20.9
Enola West Yard	20	25	20	1	2.5	1	2	900	24.5
Enola East Yard	21	17	20	1	3	1	2	800	27.6
Selkirk Yard	11	70	9	2	3	2	2	3000	33.5
Radnor Yard	13	56	10	2	3	2	1	2200	27.3
Linwood Yard	12	60	8	1	2	1	2	2200	25.6
Avon Yard	10	55	12	2	3	2	1	1800	22.4
Birmingham Yard	12	56	12	1	2	1	2	1700	28.9
Knoxville Yard	12	48	10	1	3	2	2	1550	35.9

the number of cars that each track can hold. These common operational parameters were from the recommendation data from 2013 INFORMS RAS Competition (RAS). The competition case was prepared by several experts from railroads. The values of those additional parameters are:

- Receiving track capacity: each can hold up to 120 cars.
- Classification track capacity: each can hold up to 40 cars.
- Departure track capacity: each can hold up to 120 cars.
- Minimum humping interval: 10 min between consecutive humping activities
- Technical inspection time is 30 min for both inbound and outbound trains.
- Average time to perform a single track pull: 10 min
- Average time to perform a multi-track pull: 15 min for each additional track
- Minimum and maximum train sizes are 40 cars and 100 cars, averagely are 70 cars.

3.2 Simulation Model

I use the Anylogic software as the simulation tool. Anylogic is a widely used tool for business and science simulation, and it was developed by the AnyLogic Company. It supports agent-based, discrete event, and system dynamics simulation methodologies. My simulation belongs to the discrete event simulation. Here, I gave details about the Birmingham Yard simulation, for other yards, it can be modified based on Birmingham Yard with different infrastructure features and operational parameters.

The input parameters of Birmingham Yard simulation are in Table 3.2. The simulation model time is 30 days, 24 hours each day, so total 720 hours.

Table 3.2. Input parameters of Birmingham Yard simulation

Parameters	Unit of Measure	Value
Arrival Rate	Train/hour	0.5
Size	Number of Cars/Train	(**int**) triangular(40,70,120)
Hump Engine	Count	1
Pullback Engine	Count	2
Humping Speed	Car/minute	2
Inspection Time of Inbound and outbound	Train/minute	30
Simulation Model Time	days	30

Figure 3.3 shows the Birmingham Yard simulation logic diagram, it consist of three main areas: receiving area with 12 tracks, classification area with 56 tracks and departure area with 12 tracks. I then did 30 simulation experiments. Table 3.3 summarizes the simulation outputs of dwell time and cars per day in Birmingham Yard. The minimum cars per day is 1056, and the minimum dwell time is 5.712 hours. The average dwell time is 29.395 hours, and the average cars per day is 1736.8. Figure 3.4 shows the relationship of dwell time and the volume in terms of cars per day. It suggests when cars volume is lower than a certain threshold value, the dwell time keep stable. Once its volume pasts this threshold, the dwell time increases rapidly.

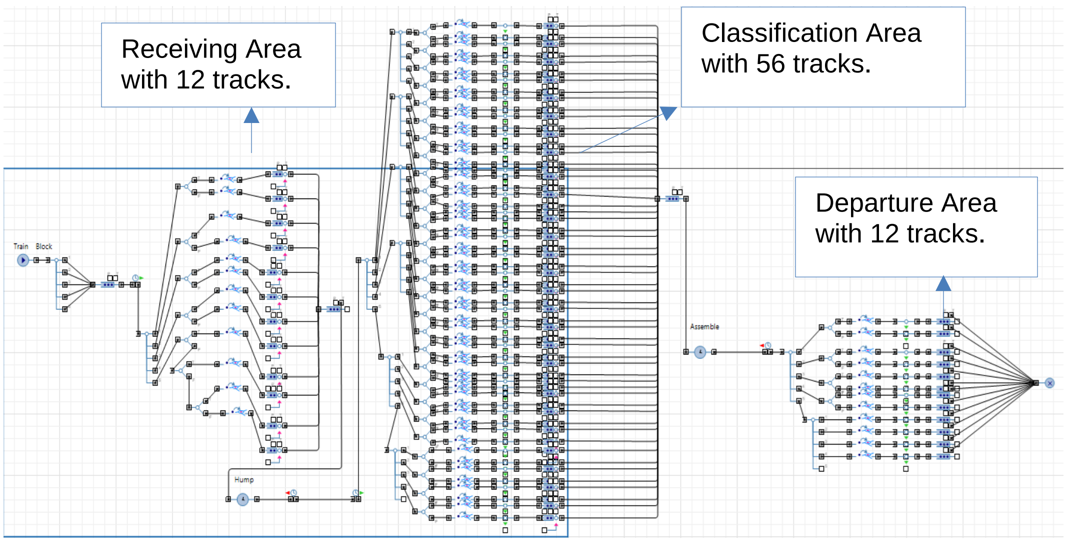

Figure 3.3. Birmingham Yard simulation logic diagram

Table 3.3. Summary of dwell time and volume simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	29.395	Mean	1,736.80
Min	5.712	Min	1,056
Max	95.528	Max	2,256
Deviation	25.884	Deviation	311.744
Mean confidence	9.65	Mean confidence	116.223
Sum	881.843	Sum	52,104

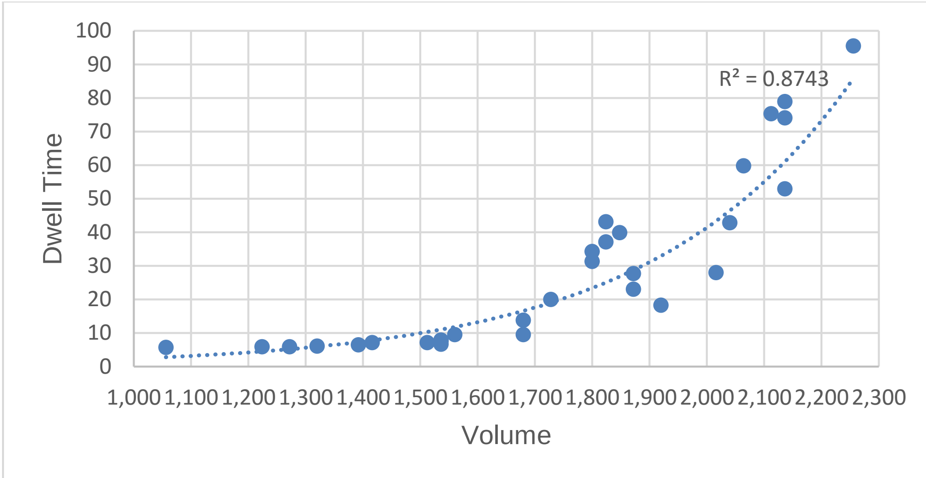

Figure 3.4. Dwell time and volume relationship of Birmingham Yard

3.3 Yard Capacity Estimation

Based on the previous definition of yard capacity, which is measured by the maximum number of rail cars can be handled per day in the yard. We can estimate each yard capacity according to their dwell time and volume relationship figures. Assuming we divide the fitting line of its figure with the range of 50 in the horizontal axis. Then capacity is the value of cars per day when its dwell time increases at least 20% from its previous adjacent point. Here in Figure 3.4, when volume is 1650, its dwell time is 16, which increases 23.1% from the dwell time of volume 1600, whose dwell time is 13. So we estimate the Birmingham yard capacity is around 1650 cars per day.

In previous, I referred to the threshold value in the volume and dwell time relationship figure, which is actually the yard capacity. 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.

CHAPTER FOUR
ANALYTICAL MODEL BASED ON BPR FUNCTION

4.1 BPR analytical model

In this section, I am going to build an analytical model for the relationship between the dwell time and cars volume based upon the simulation results. Many different types of dwell time and volume functions have been proposed and used in practice, for a review article see (Branston 1976). By far the most widely used dwell time and volume functions are the BPR (Bureau of Public Roads) functions (Roads 1964). However, the basic BPR function was used for highway transportation, later Fernandez L. et al. (2004) used the improved BPR type function Equation 4-1, which was borrowed from highway capacity studies, to model classification yard dwell time.

Equation 4-1:

$$DW_i = M_i + \alpha \left(\frac{V_i}{CAP_i}\right)^{\beta}$$

Here,

DW_i:	Average classification delay for a freight car in yard i;
M_i:	Classification delay for a freight car in yard i, in free flow conditions when there is no congestion, here, set it as the minimum dwell time;
V_i:	Flow of railcars in yard i during a period;
CAP_i:	Capacity in yard i during a period in railcars;
α, β:	Calibration parameters.

The model is simple and in general follows the same shape as Figure 2.2 with right calibration parameter value. But they did not provide the details on how to obtain the values of all parameters for any specific yard. In this paper, I'll use the data from simulation model to fit the parameters of BPR function.

The BPR function is a power function. I fit it with the following nonlinear model Equation 4-2 and based on the 30 simulation experiments results of Birmingham Yard in Table 4.1.

Equation 4-2:

$$\mathrm{D} = a \times (\tfrac{V}{C})^{b}$$

Where,

$D = DW_i$-M_i;

Table 4.1. Cars/day and dwell time simulation data

Runs	Cars/day	Dwell Time	Runs	Cars/day	Dwell Time
1	1,824	43.154	16	1,272	5.910
2	2,256	95.528	17	2,112	75.281
3	1,416	7.167	18	1,824	37.157
4	1,560	9.537	19	1,536	7.646
5	1,800	31.301	20	1,872	23.061
6	1,680	13.816	21	2,136	74.086
7	1,680	9.556	22	1,536	6.704
8	1,728	20.019	23	2,040	42.804
9	1,536	7.939	24	2,136	78.900
10	1,320	6.139	25	2,136	52.925
11	1,920	18.271	26	1,392	6.455
12	1,848	39.944	27	2,016	28.027
13	1,800	34.246	28	1,512	7.195
14	1,872	27.688	29	1,224	5.865
15	1,056	5.712	30	2,064	59.809

$a = \alpha, b = \beta;$
$\frac{V}{C} = \frac{V_i}{CAP_i}$ $(i = 1,2,..30);$

For the Birmingham Yard, M_i is set as the minimum dwell time, which is 5.712.This minimum dwell time corresponds to the condition of free flow. I then use the Gauss-Newton method with the SAS nonlinear regression procedure to find the two parameters a, b. Table 4.2 shows the results of analysis of variance, the p value is less than 0.0001, which suggests the model is significant. Table 4.3 shows the estimated a is 9.8279, and the estimated b is 7.1488.

Table 4.2. Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F value	Approx Pr > F
Model	2	34066.5	17033.2	217.89	<.0001
Error	28	2188.8	78.1719		
Uncorrected Total	30	36255.3			

Table 4.3. Parameter Estimates

Parameter	Estimate	Approx Std Err	Approximate 95% Confidence Limits	
a	9.8279	1.7437	6.2560	13.3998
b	7.1488	0.7079	5.6987	8.599

So from the statistical analysis results, the volume dwell time model can be expressed as Equation 4-3.

Equation 4-3:

$$\mathrm{D} = 9.8279 \times (V/C)^{7.1488}$$

The corresponding BPR expression is Equation 4-4.

Equation 4-4:

$$DW_i = 5.712 + 9.8279 \times (\frac{V_i}{1650})^{7.1488}$$

Where 5.712 is the delay in free flow condition, 9.8279 and 7.1488 are the calibration parameters. The yard capacity is 1650 cars per day.

4.2 Evaluate BPR analytical model

In this section, I apply statistical analysis to evaluate the BPR analytical model. First, Figure 4.1 shows the fitting plot of BPR function, which suggest the BPR model fit the yard data very well. Second, we can see the BPR accuracy from the following actual vs predicted plot Figure 4.2. These points distribute in diagonal, which suggests the predicted value is equal to the actual value.

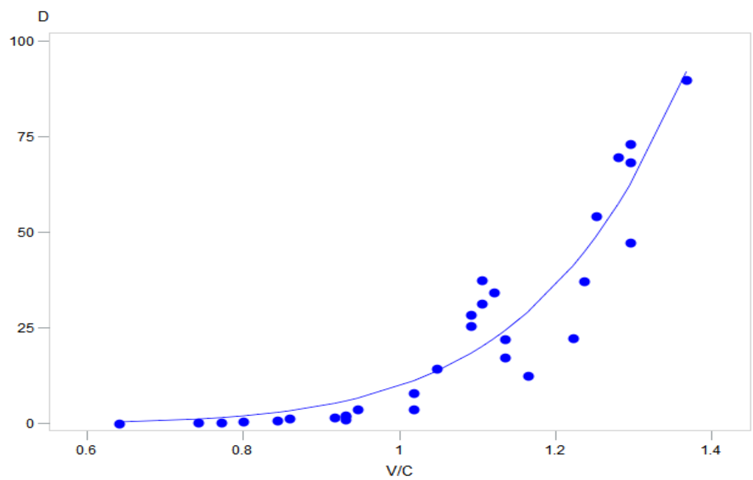

Figure 4.1. Fitting plot of BPR function

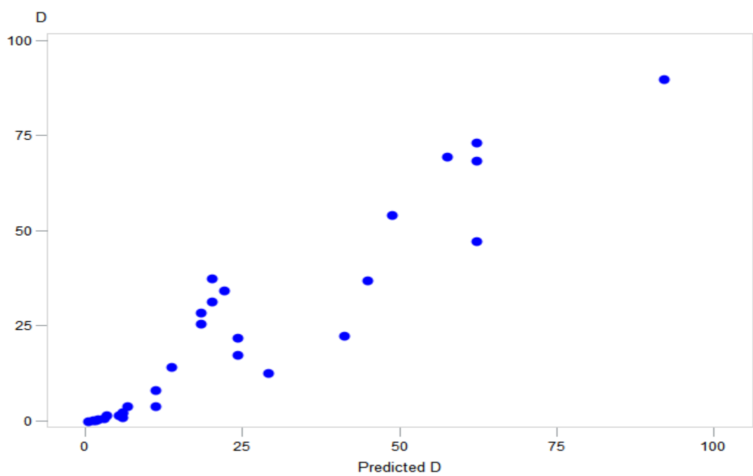

Figure 4.2. Actual vs Predicted plot

Both of the above evaluations show the BPR analytical model has good accuracy to capture the relationship between yard dwell time and cars volume. Although the above model is derived from Birmingham Yard data. We can further extend the BPR model to a more general form which could apply to all of yards. It's like Equation 4-5.

Equation 4-5:

$$DW_i = M_i + 9.83 \times \left(\frac{V_i}{CAP_i}\right)^{7.15}$$

Where 9.53 and 7.15 are the calibration parameters, M_i is the dwell time of yard i in free flow condition when there is no congestion. So for each yard, we only need to know its free flow dwell time, volume and capacity in order to apply this BPR analytical model.

CHAPTER FIVE
MODEL VALIDATION

In order to ensure the integrated simulation and analytical models is applicable to the practice, I use 15 other classification yards to verify it. The details of these yard information is in chapter 2. With these yard data, I did 30 simulation runs for each yard.

Table 5.1 and Figure 5.1 show the simulation results for Knoxville Yard. The average simulation dwell time is 38.4 hours, and its average volume is 1557 cars per day. The estimated capacity of Knoxville Yard is around 1450 cars per day.

Table 5.1. Summary of Knoxville Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	38.394	Mean	1,557.39
Min	6.072	Min	1,105.44
Max	146.225	Max	2,098.08
Deviation	35.67	Deviation	276.587
Mean confidence	13.298	Mean confidence	103.116
Sum	1,151.83	Sum	46,721.76

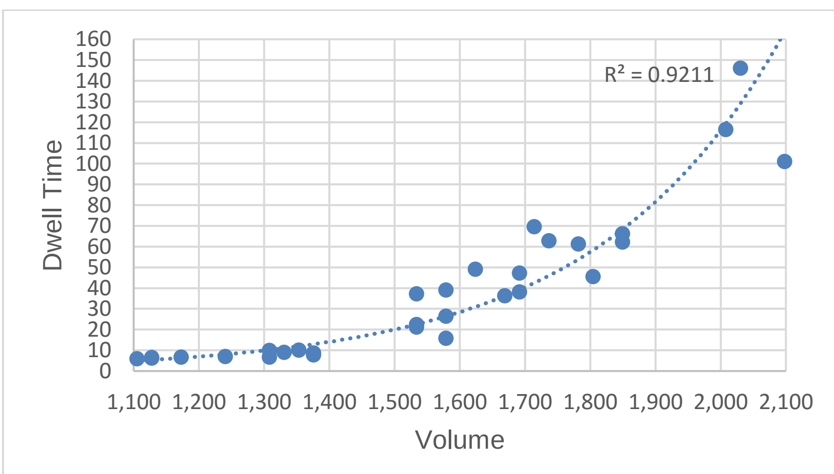

Figure 5.1. Volume and dwell time relationship of Knoxville Yard

Table 5.2 and Figure 5.2 show the simulation results for Bailey Yard. The average simulation dwell time is 45.0 hours, and its average volume is 4009 cars per day. The estimated capacity of Bailey Yard is around 3500 cars per day.

Table 5.3 and Figure 5.3 show the simulation results for J.R. Davis Yard. The average simulation dwell time is 31.3 hours, and its average volume is 2247 cars per day. The estimated capacity of J.R. Davis Yard is around 2150 cars per day.

Table 5.4 and Figure 5.4 show the simulation results for Barstow Yard. The average simulation dwell time is 37.4 hours, and its average volume is 2221 cars per day. The estimated capacity of Barstow Yard is around 2150 cars per day.

Table 5.2. Summary of Bailey Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	44.969	Mean	4,008.98
Min	5.316	Min	2,454.48
Max	113.516	Max	5,201.16
Deviation	36.496	Deviation	730.335
Mean confidence	13.606	Mean confidence	272.281
Sum	1,349.06	Sum	120,269.52

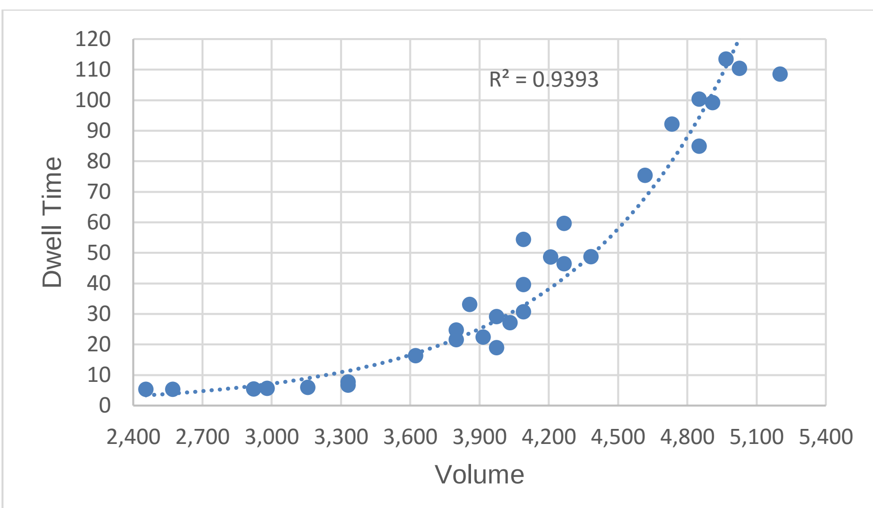

Figure 5.2. Volume and dwell time relationship of Bailey Yard

Table 5.3. Summary of J.R. Davis Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	31.273	Mean	2,246.72
Min	5.698	Min	1,468.80
Max	126.292	Max	3,166.08
Deviation	32.029	Deviation	379.976
Mean confidence	11.941	Mean confidence	141.661
Sum	938.179	Sum	67,401.60

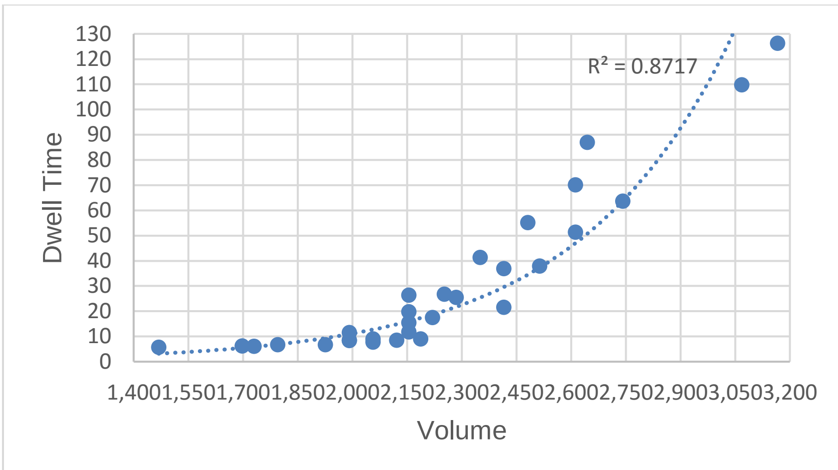

Figure 5.3. Volume and dwell time relationship of J.R. Davis Yard

Table 5.4. Summary of Barstow Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	37.398	Mean	2,220.61
Min	6.222	Min	1,664.64
Max	131.05	Max	3,002.88
Deviation	33.212	Deviation	326.342
Mean confidence	12.382	Mean confidence	121.666
Sum	1,121.95	Sum	66,618.24

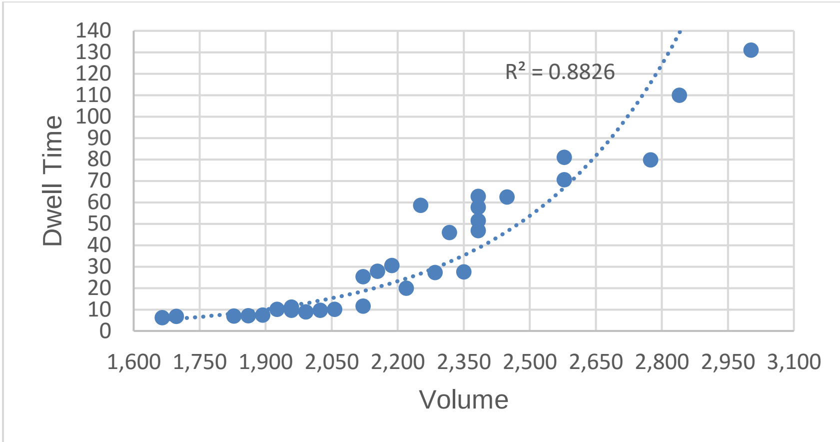

Figure 5.4. Volume and Dwell Time relationship of Barstow Yard

Table 5.5 and Figure 5.5 show the simulation results for Galesburg Yard. The average simulation dwell time is 29.9 hours, and its average volume is 2537 cars per day. The estimated capacity of Galesburg Yard is around 2350 cars per day.

Table 5.6 and Figure 5.6 show the simulation results for Northtown Yard. The average simulation dwell time is 21.3 hours, and its average volume is 1271 cars per day. The estimated capacity of Northtown Yard is around 1300 cars per day.

Table 5.7 and Figure 5.7 show the simulation results for Conway Eastbound Yard. The average simulation dwell time is 29.2 hours, and its average volume is 3088 cars per day. The estimated capacity of Conway Eastbound Yard is around 2850 cars per day.

Table 5.5. Summary of Galesburg simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	29.893	Mean	2,536.80
Min	5.505	Min	1,656
Max	76.533	Max	3,096
Deviation	21.529	Deviation	333.279
Mean confidence	8.026	Mean confidence	124.252
Sum	896.802	Sum	76,104

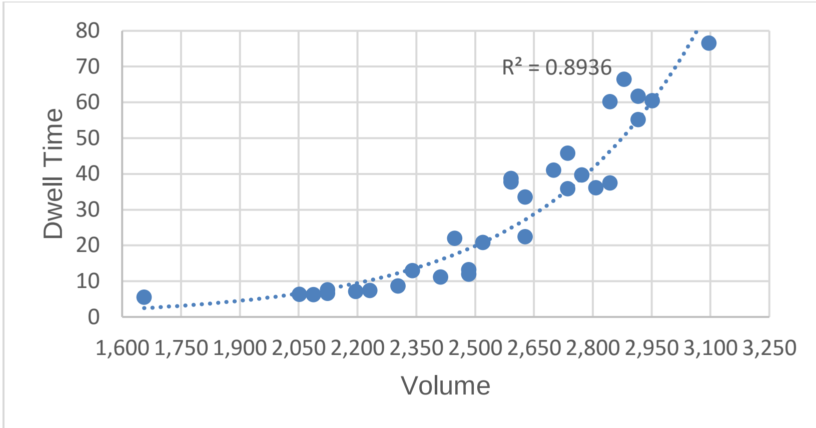

Figure 5.5. Volume and Dwell Time relationship of Galesburg Yard

Table 5.6. Summary of Northtown Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	21.286	Mean	1,271.04
Min	5.828	Min	883.2
Max	78.173	Max	1,728
Deviation	21.425	Deviation	229.814
Mean confidence	7.988	Mean confidence	85.679
Sum	638.589	Sum	38,131.20

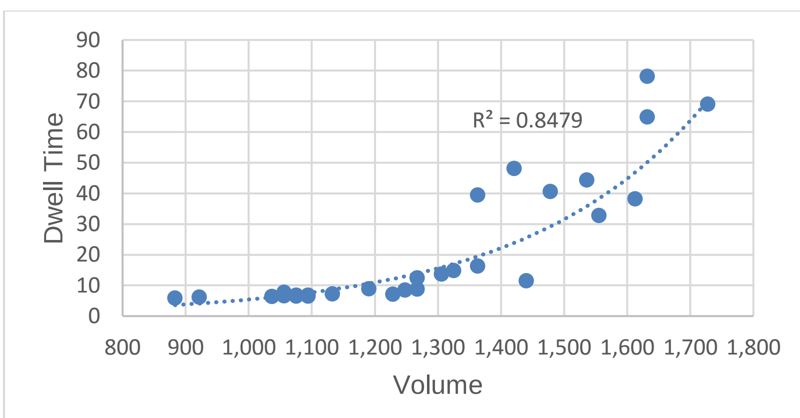

Figure 5.6. Volume and dwell time relationship of Northtown Yard

Table 5.7. Summary of Conway Eastbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	29.2	Mean	3,088.18
Min	5.301	Min	1,965.60
Max	115.289	Max	4,324.32
Deviation	30.971	Deviation	587.727
Mean confidence	11.547	Mean confidence	219.114
Sum	876.011	Sum	92,645.28

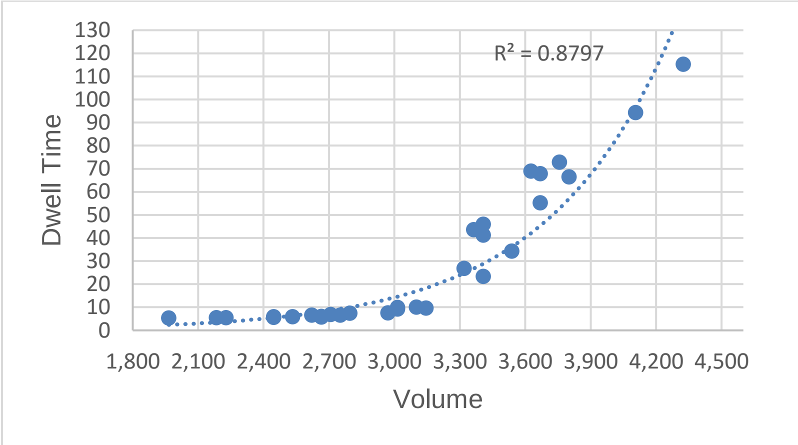

Figure 5.7. Volume and dwell time relationship of Conway Eastbound Yard

Table 5.8 and Figure 5.8 show the simulation results for Conway Westbound Yard. The average simulation dwell time is 27.2 hours, and its average volume is 3023 cars per day. The estimated capacity of Conway Westbound Yard is around 2950 cars per day.

Table 5.9 and Figure 5.9 show the simulation results for Cumberland Yard. The average simulation dwell time is 31.7 hours, and its average volume is 1358 cars per day. The estimated capacity of Conway Eastbound Yard is around 1300 cars per day.

Table 5.10 and Figure 5.10 show the simulation results for Argentine Eastbound Yard. The average simulation dwell time is 24.0 hours, and its average volume is 1227 cars per day. The estimated capacity of Argentine Eastbound Yard is around 1250 cars per day.

Table 5.8. Summary of Conway Westbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	27.197	Mean	3,022.66
Min	5.402	Min	2,052.96
Max	97.009	Max	4,062.24
Deviation	28.467	Deviation	559.071
Mean confidence	10.613	Mean confidence	208.431
Sum	815.909	Sum	90,679.68

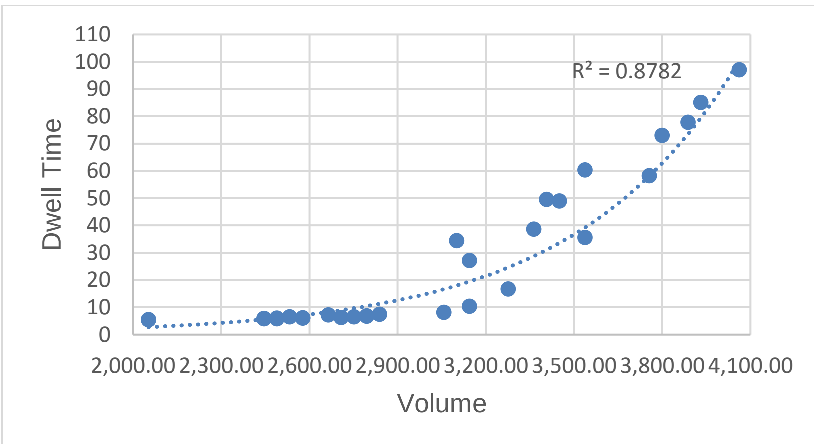

Figure 5.8. Volume and dwell time relationship of Conway Westbound Yard

Table 5.9. Summary of Cumberland Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	31.677	Mean	1,358.08
Min	6.546	Min	960
Max	117.473	Max	1,708.80
Deviation	28.55	Deviation	200.861
Mean confidence	10.644	Mean confidence	74.884
Sum	950.301	Sum	40,742.40

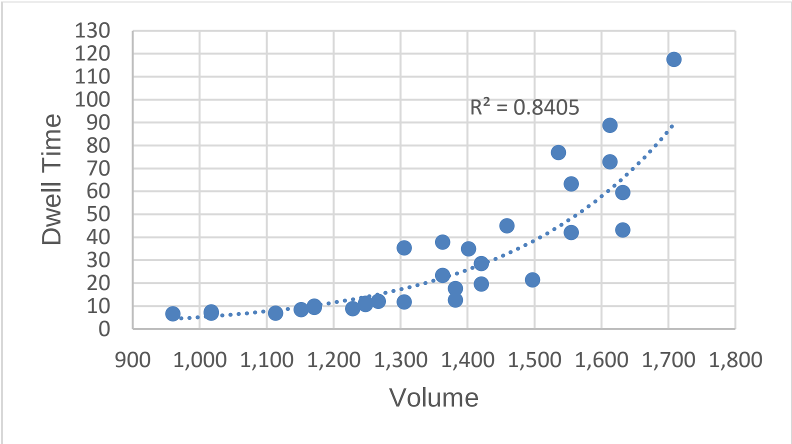

Figure 5.9. Volume and dwell time relationship of Cumberland Yard

Table 5.10. Summary of Argentine Eastbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	23.972	Mean	1,226.75
Min	6.198	Min	862.008
Max	90.577	Max	1,706.42
Deviation	22.836	Deviation	203.219
Mean confidence	8.514	Mean confidence	75.763
Sum	719.167	Sum	36,802.46

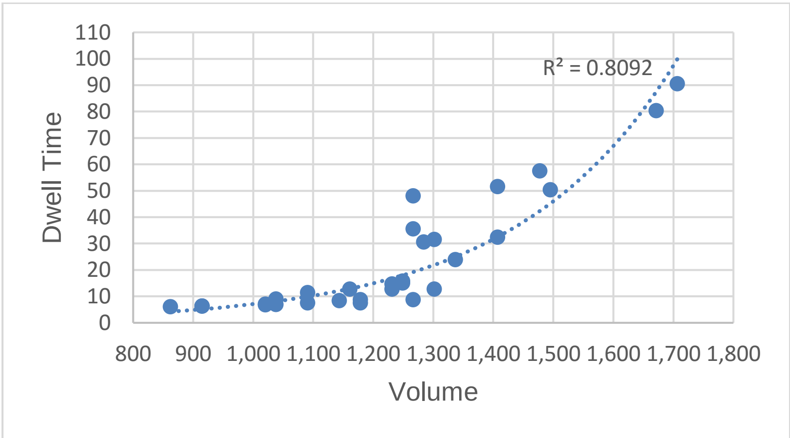

Figure 5.10. Volume and dwell time relationship of Argentine Eastbound Yard

Table 5.11 and Figure 5.11 show the simulation results for West Colton Yard. The average simulation dwell time is 20.5 hours, and its average volume is 1218 cars per day. The estimated capacity of West Colton Yard is around 1250 cars per day.

Table 5.12 and Figure 5.12 show the simulation results for Argentine Westbound Yard. The average simulation dwell time is 35.4 hours, and its average volume is 2764 cars per day. The estimated capacity of Argentine Westbound Yard is around 2650 cars per day.

Table 5.13 and Figure 5.13 show the simulation results for Enola Westbound Yard. The average simulation dwell time is 24.0 hours, and its average volume is 861 cars per day. The estimated capacity of Enola Westbound Yard is around 850 cars per day.

Table 5.11. Summary of West Colton Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	20.499	Mean	1,218.14
Min	6.121	Min	842.112
Max	77.027	Max	1,631.59
Deviation	20.759	Deviation	237.518
Mean confidence	7.739	Mean confidence	88.551
Sum	614.981	Sum	36,544.15

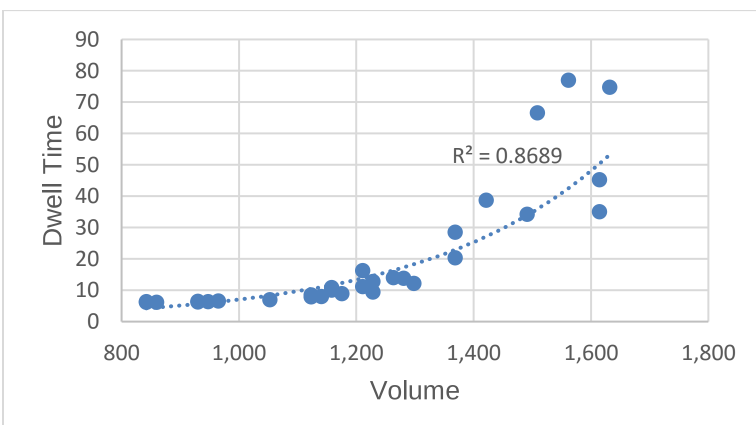

Figure 5.11. Volume and dwell time relationship of West Colton Yard

Table 5.12. Summary of Argentine Westbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	35.434	Mean	2,763.52
Min	5.434	Min	1,795.20
Max	117.032	Max	3,753.60
Deviation	34.461	Deviation	535.509
Mean confidence	12.847	Mean confidence	199.646
Sum	1,063.01	Sum	82,905.60

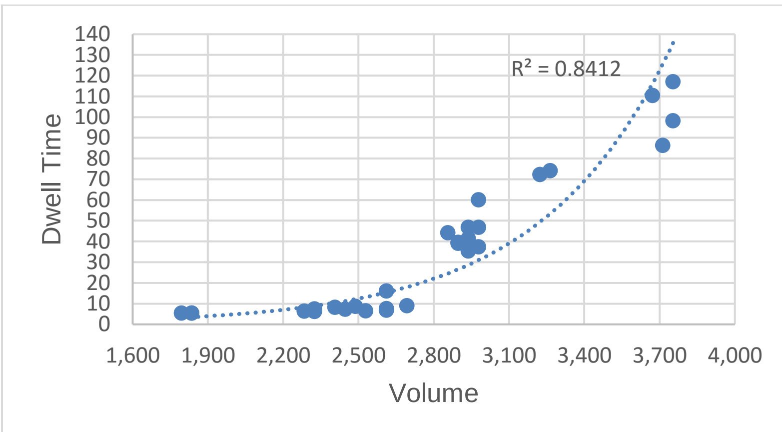

Figure 5.12. Volume and Dwell Time relationship of Argentine Westbound Yard

Table 5.13. Summary of Enola Westbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	24.001	Mean	861.272
Min	6.149	Min	558.312
Max	92.853	Max	1,155.58
Deviation	24.054	Deviation	178.234
Mean confidence	8.968	Mean confidence	66.449
Sum	720.018	Sum	25,838.16

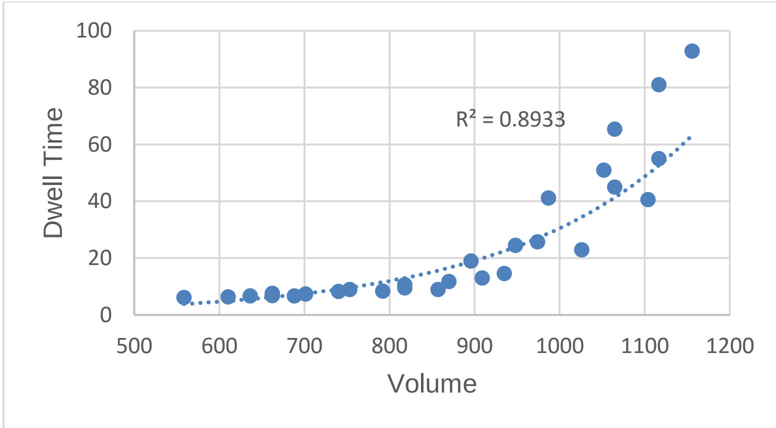

Figure 5.13. Volume and dwell time relationship of Enola Westbound Yard

Table 5.14 and Figure 5.14 show the simulation results for Enola Eastbound Yard. The average simulation dwell time is 29.5 hours, and its average volume is 856 cars per day. The estimated capacity of Enola Eastbound Yard is around 750 cars per day.

Table 5.15 and Figure 5.15 show the simulation results for Selkirk Yard. The average simulation dwell time is 35.8 hours, and its average volume is 3002 cars per day. The estimated capacity of Selkirk Yard is around 3000 cars per day.

Table 5.16 and Figure 5.16 show the simulation results for Radnor Yard. The average simulation dwell time is 26.7 hours, and its average volume is 2154 cars per day. The estimated capacity of Radnor Yard is around 2100 cars per day.

Table 5.17 and Figure 5.17 show the simulation results for Linwood Yard. The average simulation dwell time is 25.4 hours, and its average volume is 2210 cars per day. The estimated capacity of Linwood Yard is around 2200 cars per day.

Table 5.18 and Figure 5.18 show the simulation results for Avon Yard. The average simulation dwell time is 22.9 hours, and its average volume is 1850 cars per day. The estimated capacity of Avon Yard is around 1900 cars per day.

Table 5.14. Summary of Enola Eastbound Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	29.512	Mean	856.128
Min	6.769	Min	564.48
Max	79.736	Max	1,128.96
Deviation	24.012	Deviation	141.942
Mean confidence	8.952	Mean confidence	52.918
Sum	885.346	Sum	25,683.84

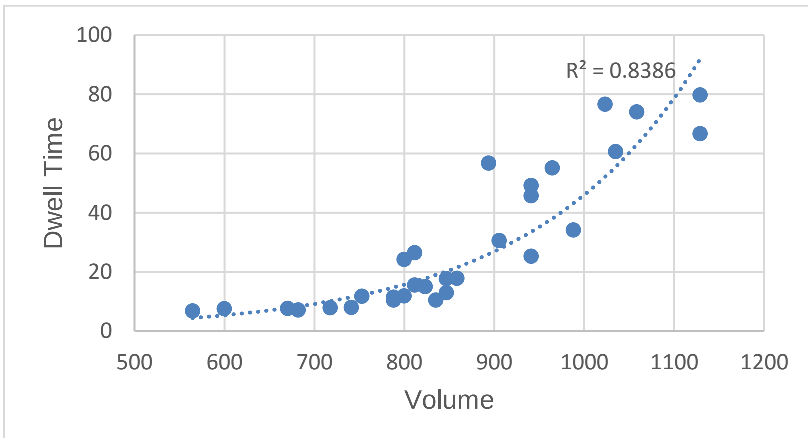

Figure 5.14. Volume and dwell time relationship of Enola Eastbound Yard

Table 5.15. Summary of Selkirk Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	35.843	Mean	3,001.98
Min	5.516	Min	1,985.28
Max	123.731	Max	4,105.92
Deviation	35.218	Deviation	548.491
Mean confidence	13.13	Mean confidence	204.486
Sum	1,075.29	Sum	90,059.52

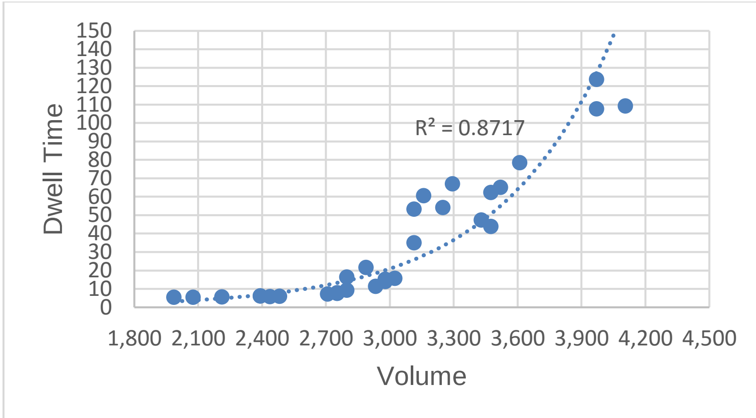

Figure 5.15. Volume and Dwell Time relationship of Selkirk Yard

Table 5.16. Summary of Radnor Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	26.654	Mean	2,153.84
Min	5.758	Min	1,528.80
Max	106.197	Max	2,776.80
Deviation	29.045	Deviation	343.198
Mean confidence	10.828	Mean confidence	127.95
Sum	799.615	Sum	64,615.20

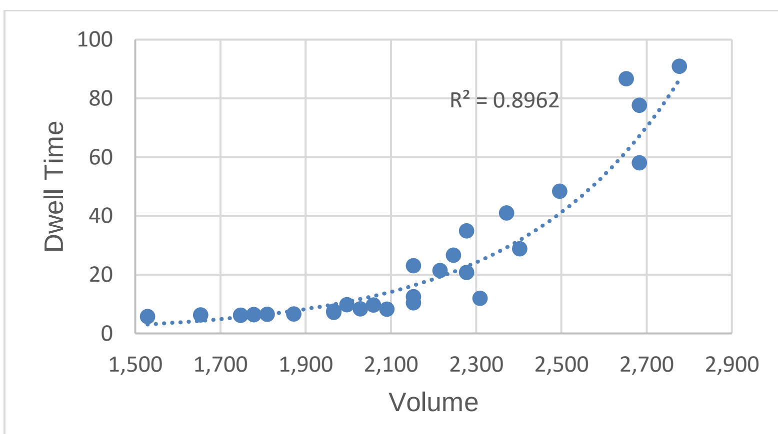

Figure 5.16. Volume and dwell time relationship of Radnor Yard

Table 5.17. Summary of Linwood Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	25.388	Mean	2,210
Min	5.72	Min	1,560
Max	81.997	Max	2,808
Deviation	23.381	Deviation	362.75
Mean confidence	8.717	Mean confidence	135.239
Sum	761.652	Sum	66,300

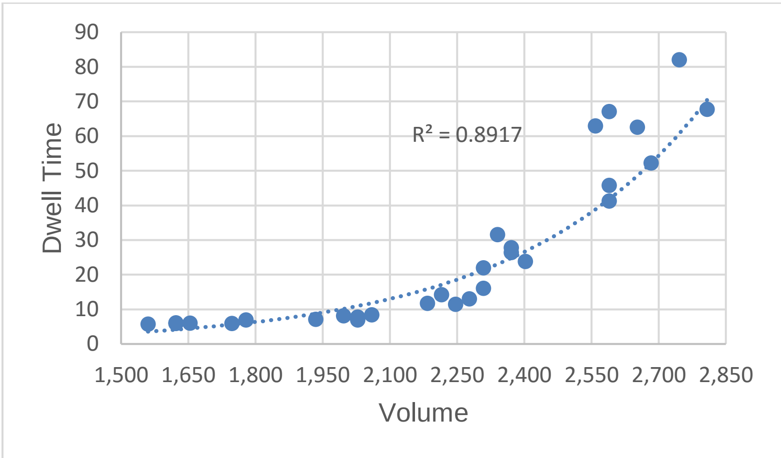

Figure 5.17. Volume and dwell time relationship of Linwood Yard

Table 5.18. Summary of Avon Yard simulation results

Dwell Time:		Volume:	
Count	30	Count	30
Mean	22.898	Mean	1,849.95
Min	5.778	Min	1,346.40
Max	76.38	Max	2,423.52
Deviation	22.146	Deviation	297.358
Mean confidence	8.256	Mean confidence	110.86
Sum	686.934	Sum	55,498.61

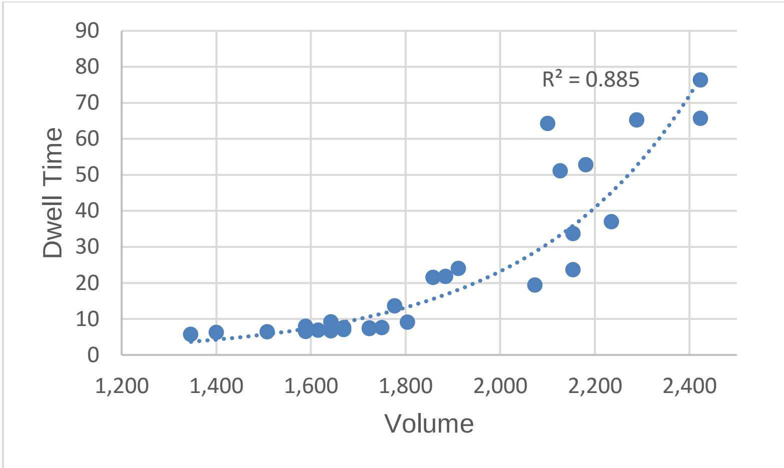

Figure 5.18. Volume and dwell time relationship of Avon Yard

With the above simulation results for each yard, I then estimate their yard capacity with the cars volume and dwell time relationship figure as discussed in last section. The capacity for each yard is summarized in Table 5.19.

Table 5.19. Estimated yard capacity

Yards	RecT (X_1)	ClassT (X_2)	DepT (X_3)	Hump Nums (X_4)	Hump Speed (X_5)	Hump Engines (X_6)	Pull Engines (X_7)	Cap
Bailey Yard(UP)	17	114	16	1	4	2	1	3500
J.R. Davis(UP)	8	55	8	1	3	2	2	2150
Barstow Yard(BNSF)	10	48	10	2	3	2	1	2150
Galesburg Yard(BNSF)	17	62	17	1	3	2	1	2350
Northtown Yard(BNSF)	12	47	9	1	2.5	1	1	1300
Conway Eastbound Yard(NS)	10	54	10	2	3	2	2	2850
Conway Westbound Yard(NS)	11	53	10	2	4	2	2	2950
Cumberland Yard (CSX)	8	33	8	1	4	2	2	1300
Argentine Eastbound Yard(BNSF)	23	48	14	1	2	1	1	1250
Argentine Westbound Yard(BNSF)	16	53	14	1	4	2	2	2650
West Colton Yard(UP)	9	48	12	1	2	1	1	1250
Enola Westbound Yard(NS)	20	25	20	1	2.5	1	2	850
Enola Eastbound Yard(NS)	21	17	20	1	3	1	2	750
Selkirk Yard (CSX)	11	70	9	2	3	2	2	3000
Radnor Yard(CSX)	13	56	10	2	3	2	1	2100
Linwood Yard (NS)	12	60	8	1	2	1	2	2200
Avon Railyard (CSX)	10	55	12	2	3	2	1	1900
Birmingham Yard(NS)	12	56	12	1	2	1	2	1650
Knoxville Yard(NS)	12	48	10	1	3	2	2	1450

5.1 Identification of key factors for yard capacity

Based on the data from Table 5.19, I use JMP's Screening Platform to identify significant factors. The advantage of this method is that it can construct factor interactions automatically. This is in contrast to other fit models, where you need to manually specify the interactions that you want to include in your model.

Figure 5.19 shows the screening report for yard capacity. Factors whose individual p-value is less than 0.10 are highlighted. Both individual and simultaneous p-values are shown. Those that are less than 0.05 are shown with an asterisk.

Screening for Capacity

Contrasts

Term	Contrast	Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
ClassT (X2)	607.435	10.45	<.0001*	0.0008*
Hump engines (X6)	286.189	4.92	0.0024*	0.0232*
Pull engines (X7)	163.565	2.81	0.0218*	0.2181
Hump Nums (X4)	186.467	3.21	0.0133*	0.1446
Hump Speed (X5)	78.107	1.34	0.1716	0.9335
ReceiveT (X1)	31.744	0.55	0.6136	1.0000
DeparT (X3)	-13.913	-0.24	0.8241	1.0000
ClassT (X2)*ClassT (X2)	-147.220 *	-2.53	0.0276*	0.2660
ClassT (X2)*Hump engines (X6)	24.433 *	0.42	0.6978	1.0000
ClassT (X2)*Pull engines (X7)	29.742 *	0.51	0.6375	1.0000
Hump engines (X6)*Pull engines (X7)	-17.989 *	-0.31	0.7744	1.0000
ClassT (X2)*Hump Nums (X4)	-91.158 *	-1.57	0.1180	0.8162
Pull engines (X7)*Hump Nums (X4)	97.910 *	1.68	0.0975	0.7418
ClassT (X2)*Hump Speed (X5)	-34.718 *	-0.60	0.5774	1.0000
Hump engines (X6)*Hump Speed (X5)	42.778 *	0.74	0.4361	1.0000
Pull engines (X7)*Hump Speed (X5)	-24.900 *	-0.43	0.6926	1.0000
Hump Nums (X4)*Hump Speed (X5)	-100.782 *	-1.73	0.0896	0.7056
Hump Speed (X5)*Hump Speed (X5)	-21.250 *	-0.37	0.7365	1.0000

Figure 5.19. Screening report for capacity

A t-ratio is calculated using Lenth's PSE (pseudo-standard error). The Lenth PSE is shown below the half normal plot Figure 5.20. The half normal plot shows the absolute value of the contrasts plotted against the absolute value of quantiles for the half-normal distribution. Significant effects appear separated from the line towards the upper right of the graph.

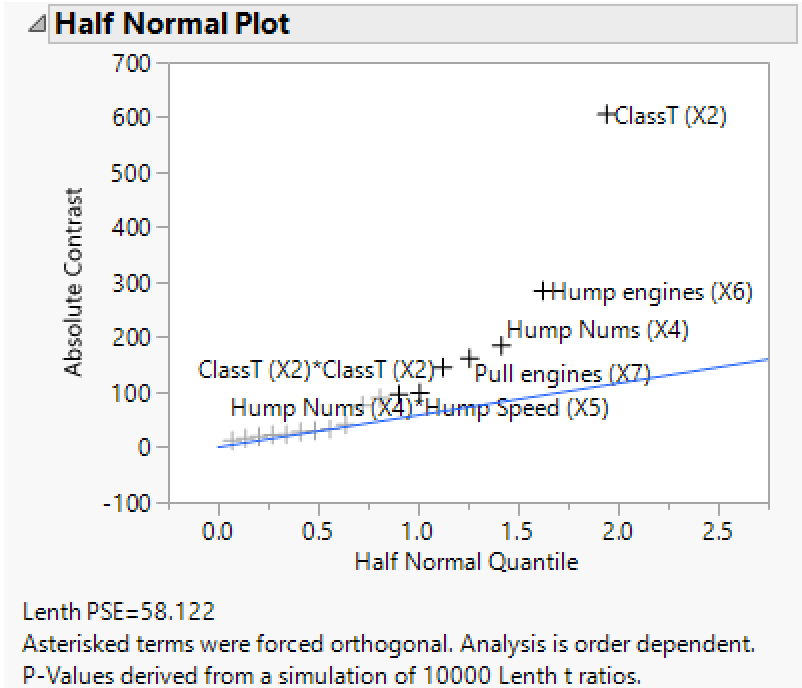

Figure 5.20. Half normal plot

Note that in Figure 5.19, the Hump Nums*Hump Speed interaction is highlighted, but the Hump Speed main effect is not. According to the principle of Effect Heredity, the Hump Speed main effect should be added to the model.
The screening design shows the number of humps, classification track, hump engines, pull engines, and the interaction of Pull engines*Hump Nums, Hump Nums*Hump Speed and the quadratic term ClassT*ClassT are significant factors.

5.2 Development of parametric yard capacity models

Based on the above screening results, I am going to build the yard capacity model with these significant factors. Specifically, I used the Standard Least Square model to fit the data of yard capacity and these significant factors. Table 5.20 shows the summary of fit, the R square is 0.933, Table 5.21 shows the analysis of variance, its p value is less than 0.0001. Both suggest the model is significant. Table 5.22 gave the estimated value for each significant factors.

Table 5.20. Summary of fit

RSquare	0.933107
RSquare Adj	0.879592
Root Mean Square Error	270.416
Mean of Response	1978.947
Observations (or Sum Wgts)	19

Table 5.21. Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	8	10200331	1275041	17.4365
Error	10	731248	73125	**Prob > F**
C. Total	18	10931579		<.0001*

Table 5.22. Parameter Estimates

Term	**Estimate**	**Std Error**	**Lower 95%**	**Upper 95%**
Intercept	-1903.857	478.9996	-2971.135	-836.5794
ClassT (X2)	35.507037	5.916738	22.323722	48.690351
Hump engines (X6)	-188.6323	380.3213	-1036.041	658.77643
Pull engines (X7)	345.07574	142.4512	27.674725	662.47676
Hump Nums (X4)	528.71035	205.8016	70.155819	987.26489
(ClassT (X2)-52.7368)*(ClassT (X2)-52.7368)	-0.215988	0.135794	-0.518557	0.0865806
(Pull engines (X7)-1.57895)*(Hump Nums (X4)-1.31579)	350.72021	321.3844	-365.3688	1066.8092
(Hump Nums (X4)-1.31579)*(Hump Speed (X5)-2.94737)	-124.845	416.9341	-1053.832	804.14197
Hump Speed (X5)	397.64224	213.2721	-77.55762	872.84209

The prediction profiler Figure 5.21 shows with the increase of classification tracks, pull engines, the number of humps and hump speed, the yard capacity will increase. However, only increasing the number of hump engines, the yard capacity couldn't increase, it may because the humping process is not a bottleneck of classification yard operations. When the number of classification tracks are large enough, the effect of it on yard capacity is limited. In addition, from the interaction profiles of Figure 5.22, we can see the interaction effect of Pull engines*Hump Nums and Hump Nums*Hump Speed. When the number of humps is one, the effect of pull engine on yard capacity is less than the effect of pull engine when there are two humps.

Figure 5.21. Prediction profiler

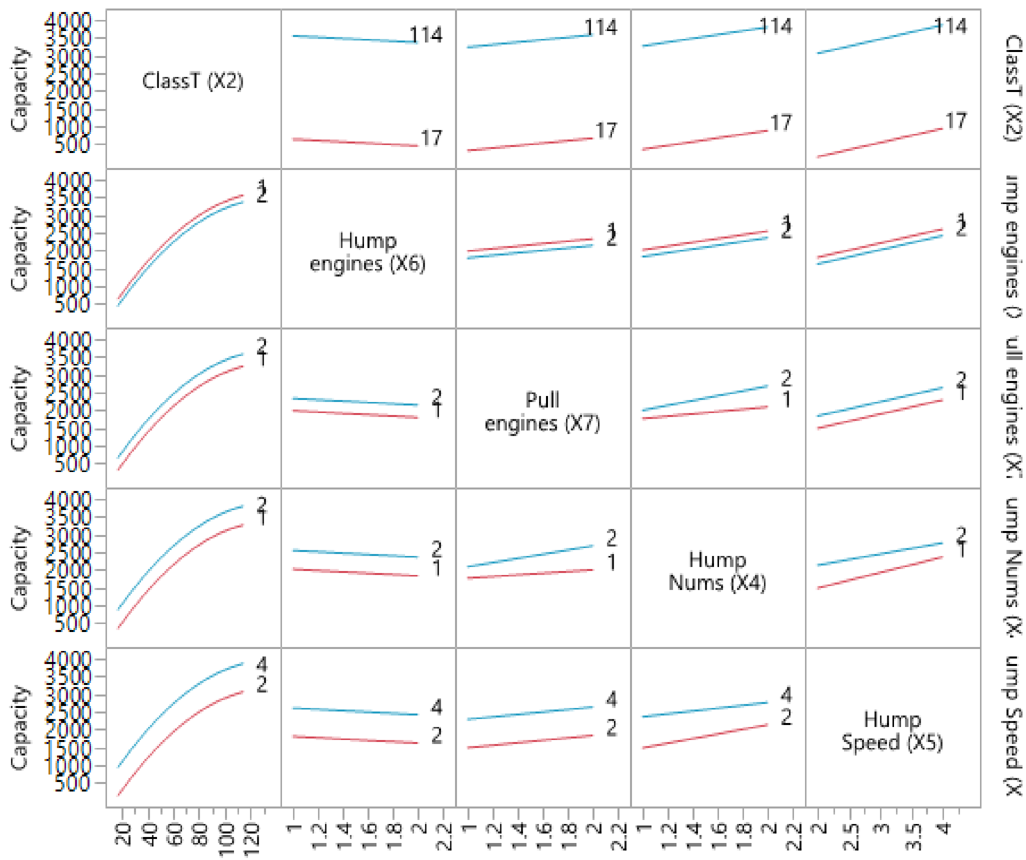

Figure 5.22. Interaction profiles

From the parameter estimation results, the yard capacity can be expressed as Equation 5-1.

Equation 5-1:

$$Cap = -0.22{X_2}^2 - 124.85X_4X_5 + 350.72X_4X_7 + 58.72X_2 + 342.88X_4 + 562.44X_5 - 188.63X_6 - 117.87X_7 - 1657.03$$

Where X_2 is classification track, X_4 is hump numbers, X_5 is hump speed, X_6 is hump engine and X_7 is pull engine.

Now, we can use the fitted model to predict the yard capacity based on these yard features. Figure 5.23 shows the comparison of predicted yard capacity and the actual yard capacity. The blue line falls outside the bounds of the 95% confidence curves (red-dotted lines), which tells you the model is significant. The model p-value< 0.0001, RSq, and RMSE appear below the plot. The RMSE is an estimate of the standard deviation.

Finally, we use the yard capacity model expression Equation 5-1 and dwell time analytical model Equation 4-5 to calculate the average dwell time for each yard. Table 5.23 shows the calculated, simulation and practical dwell time for each yard, and the predicted capacity for each yard based on the yard capacity model. I then calculate the R-square for analytical and simulation model related to the practical value. The analytical R square is 0.84, and the simulation R square is 0.92. Both show a relative good prediction accuracy. We can also see this from Figure 5.24, the analytical dwell time and simulation dwell time are good approximation of the practical dwell time.

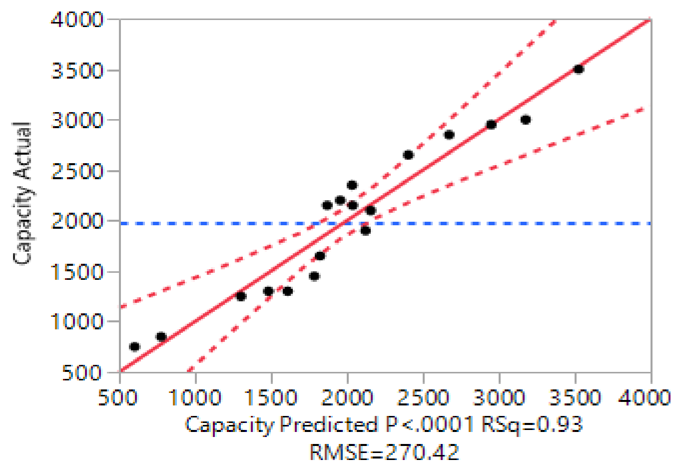

Figure 5.23. Actual by predicted yard capacity plot

Table 5.23. Calculated, simulated and practical dwell time for each yard

Yards	Volume	Predicted Capacity	Calculated Dwell Time	Simulation Dwell Time	Practical Dwell Time
Bailey Yard(UP)	4500	3526	46.5	45.0	43.5
J.R. Davis(UP)	2200	2038	28.7	31.3	30.4
Barstow Yard(BNSF)	2200	1870	37.6	37.4	37.6
Galesburg Yard(BNSF)	2600	2035	32.2	29.9	29.8
Northtown Yard(BNSF)	1350	1484	20.8	21.3	23.8
Conway Eastbound Yard(NS)	3000	2673	27.7	29.2	27.3
Conway Westbound Yard(NS)	3000	2950	26.5	27.2	28.1
Cumberland Yard (CSX)	1300	1611	28.6	31.7	29.5
Argentine Eastbound Yard(BNSF)	1200	1303	21.7	24.0	21.2
Argentine Westbound Yard(BNSF)	2800	2405	34.6	35.4	38.7
West Colton Yard(UP)	1200	1303	21.6	20.5	20.9
Enola Westbound Yard(NS)	900	778	23.1	24.0	24.5
Enola Eastbound Yard(NS)	800	603	31.4	29.5	27.6
Selkirk Yard (CSX)	3000	3177	32.0	35.8	33.5
Radnor Yard(CSX)	2200	2157	26.1	26.7	27.3
Linwood Yard (NS)	2200	1957	28.4	25.4	25.6
Avon Railyard (CSX)	1800	2123	18.8	22.9	22.4
Birmingham Yard(NS)	1700	1824	31.6	29.4	28.9
Knoxville Yard(NS)	1550	1786	39.7	38.4	35.9

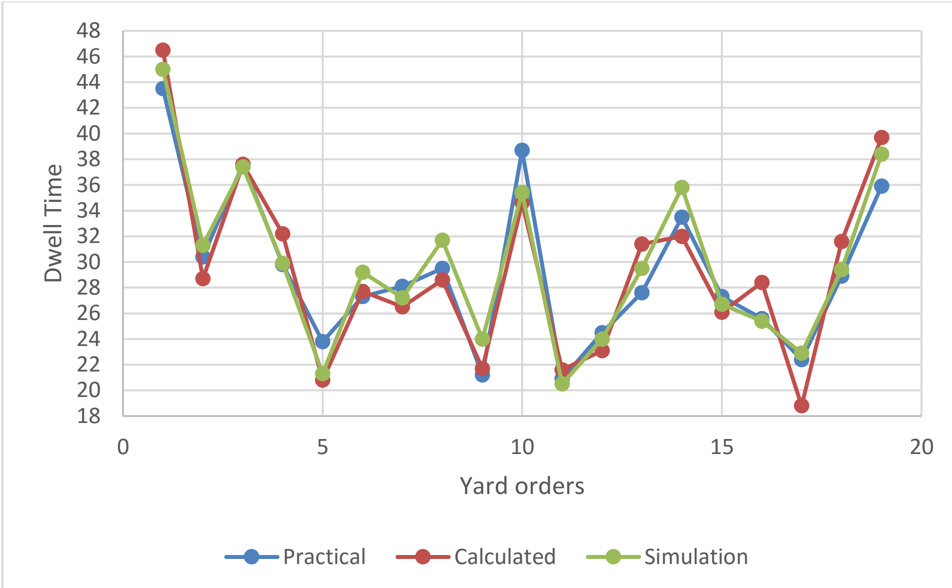

Figure 5.24. Comparison of practical, calculated and simulated dwell time

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

In this thesis, I built a simulation model to mimic the classification yard operation. Then I did 30 simulation experiments, by doing experiments, it help me generate enough data sets of volume and dwell time. Based on these data sets, I developed an analytical model with the fundamental BPR function. According to results of statistical analysis, the analytical model is very flexible and accurate. Finally, I validate the simulation model and analytical model with the practical data from other classification yards. The validation shows my yard capacity model has good accuracy in real world. This model captures the relationship between cars volume and dwell time, which shows if the cars volume is less than the yard capacity, the dwell time is small. What's more, as long as the yard capacity could satisfy the demand in terms of cars volume, the increase of volume could increase the dwell time very much, dwell time keeps relative stable. However, once the cars volume passes the yard capacity, the dwell time will increase sharply. Nowadays, because of the increasing demand of railroad freight transportation, most of the dwell time in each yard is over 30 hours, that's a big barrier for railroad efficient operations.

With the developed model in my thesis, it would help decision maker understand and make use of the capacity of existing yard infrastructure, also it could be used to justify capital investment in the yard operation. Specifically, it could help:

- Estimate the yard capacity with these relational yard parameters.
- Predict the dwell time based on the daily car volume.
- Identify the priority to expand capacity.

However, there are also several aspects could be further studied from this paper. One of the most important studies is how to incorporate this yard capacity model into the whole network. So we can analyze the relationship between cars volume and dwell time in the whole railway network, and decrease the total railroad network dwell time.

LIST OF REFERENCES

Abacoumkin, C. and A. Ballis (2004). "Development of an expert system for the evaluation of conventional and innovative technologies in the intermodal transport area." European Journal of Operational Research **152**(2): 410-419.

Abril, M., et al. (2008). "An assessment of railway capacity." Transportation Research Part E: Logistics and Transportation Review **44**(5): 774-806.

Ahuja, R. K., et al. (2007). "Solving real-life railroad blocking problems." Interfaces **37**(5): 404-419.

Assad, A. A. (1980). "Models for rail transportation." Transportation Research Part A: General **14**(3): 205-220.

Barnhart, C., et al. (2000). "Railroad blocking: A network design application." Operations Research **48**(4): 603-614.

Branston, D. (1976). "Link capacity functions: A review." Transportation Research **10**(4): 223-236.

Bussieck, M. R., et al. (1997). "Discrete optimization in public rail transport." Mathematical programming **79**(1-3): 415-444.

Carrtracks. "UP West Colton Yard." from http://www.carrtracks.com/cala533spwc.htm.

Cordeau, J.-F., et al. (1998). "A survey of optimization models for train routing and scheduling." Transportation Science **32**(4): 380-404.

Crainic, T., et al. (1984). "A tactical planning model for rail freight transportation." Transportation science **18**(2): 165-184.

Crainic, T. G., et al. (1990). "A model for the strategic planning of national freight transportation by rail." Transportation Science **24**(1): 1-24.

Crane, R. R., et al. (1955). "An analysis of a railroad classification yard." Journal of the Operations Research Society of America **3**(3): 262-271.

D'Ariano, A. and M. Pranzo (2009). "An advanced real-time train dispatching system for minimizing the propagation of delays in a dispatching area under severe disturbances." Networks and Spatial Economics **9**(1): 63-84.

Dick, C. T. and J. R. Dirnberger (2014). Advancing the science of yard design and operations with the CSX hump yard simulation system. 2014 Joint Rail Conference, American Society of Mechanical Engineers.

Dirnberger, J. and C. Barkan (2007). "Lean railroading for improving railroad classification terminal performance: bottleneck management methods." Transportation Research Record: Journal of the Transportation Research Board(1995): 52-61.

Donwinter. "CSX Radnor Yard." from http://www.donwinter.com/Railroad%20Infrastructure%20and%20Traffic%20Data/Trunk%20Routes/Pan%20American%20Route%20%28L&N%29/Places/Radnor%20Yard.htm.

Donwinter. "Northtown Yard." from http://www.donwinter.com/Railroad%20Infrastructure%20and%20Traffic%20Data/Regions/Twin%20Cities/Places/Northtown%20Yard.htm.

Eakin, K., et al. (2008). "A Study of Competition in the US Freight Railroad Industry and Analysis of Proposals that Might Enhance Competition. Executive Summary."

English, G. (1977). An analytic model for the analysis of single track railway capacity. Int. Symp. on Travel Supply Models, Montreal.

Fernández L, J. E., et al. (2004). "A strategic model of freight operations for rail transportation systems." Transportation Planning and Technology **27**(4): 231-260.

Ferreira, L. and J. Sigut (1995). "Modelling intermodal freight terminal operations." Road and Transport Research: a journal of Australian and New Zealand research and practice **4**(4): 4-16.

Gatto, M., et al. (2009). Shunting for dummies: An introductory algorithmic survey. Robust and Online Large-Scale Optimization, Springer**:** 310-337.

Hauser, A. and J. Maue (2010). Experimental evaluation of approximation and heuristic algorithms for sorting railway cars. Experimental Algorithms, Springer**:** 154-165.

Jacob, R., et al. (2011). "Multistage methods for freight train classification." Networks **57**(1): 87-105.

Javadian, N., et al. (2011). "Using simulated annealing for determination of the capacity of yard stations in a railway industry." Applied Soft Computing **11**(2): 1899-1907.

Jha, K. C., et al. (2008). "New approaches for solving the block-to-train assignment problem." Networks **51**(1): 48-62.

Li, H., et al. (2014). Optimization of railcar connection plan in a classification yard. Transportation research board 93rd annual meeting.

Lin, E. and C. Cheng (2011). Simulation and analysis of railroad hump yards in North America. Proceedings of the Winter Simulation Conference, Winter Simulation Conference.

Marinov, M. and J. Viegas (2009). "A simulation modelling methodology for evaluating flat-shunted yard operations." Simulation Modelling Practice and Theory **17**(6): 1106-1129.

Márton, P., et al. (2009). An improved train classification procedure for the hump Yard Lausanne Triage. OASIcs-OpenAccess Series in Informatics, Schloss Dagstuhl-Leibniz-Zentrum für Informatik.

Oliveira, E. and B. M. Smith (2000). "A job-shop scheduling model for the single-track railway scheduling problem." RESEARCH REPORT SERIES-UNIVERSITY OF LEEDS SCHOOL OF COMPUTER STUDIES LU SCS RR(21).

Petering, M. E. (2009). "Effect of block width and storage yard layout on marine container terminal performance." Transportation Research Part E: Logistics and Transportation Review **45**(4): 591-610.

Petersen, E. (1974). "Over-the-road transit time for a single track railway." Transportation Science **8**(1): 65-74.

Petersen, E. (1975). "Interference delays on a partially double-tracked railway with intermediate signalling." Publication of: Cross (Richard B) Company **16**(1).

Petersen, E. (1977). "Railyard modeling: Part II. The effect of yard facilities on congestion." Transportation Science **11**(1): 50-59.

Railroads, A. o. A. (2015). The Environmental Benefits of Moving Freight by Rail.

RAS "2013 INFROMS RAS Competition."

RAS. "2014 INFORMS RAS Problem Solving Competition." from https://www.informs.org/Community/RAS/Problem-Solving-Competition/2014-RAS-Problem-Solving-Competition.

Roads, U. B. O. P. (1964). "Traffic Assignment Manual." US Department of Commerce, Washington, DC.

RPM. "Railroad Performance Measures." from http://www.railroadpm.org/home/rpm.aspx.

Sayarshad, H. R. and K. Ghoseiri (2009). "A simulated annealing approach for the multi-periodic rail-car fleet sizing problem." Computers & Operations Research **36**(6): 1789-1799.

Sayarshad, H. R. and R. Tavakkoli-Moghaddam (2010). "Solving a multi periodic stochastic model of the rail–car fleet sizing by two-stage optimization formulation." Applied Mathematical Modelling **34**(5): 1164-1174.

Shi, T. and X. Zhou (2015). "A mixed integer programming model for optimizing multi-level operations process in railroad yards." Transportation Research Part B: Methodological **80**: 19-39.

Systematics, C. (2007). National rail freight infrastructure capacity and investment study, Cambridge Systematics.

Szpigel, B. (1972). Train scheduling, unpublished M. Sc, Thesis, Pontificia Universidade Catolica of Rio de Janeiro, Brazil.

Thomet, M. (1971). "A combinatorial search approach to the freight scheduling problem." Dept. of Elec. Eng, Carnegie Mellon University.

Turnquist, M. A. and M. S. Daskin (1982). "Queuing models of classification and connection delay in railyards." Transportation Science **16**(2): 207-230.

UP. "UP Bailey Yard." from http://www.up.com/aboutup/facilities/bailey_yard/.

UP. "UP J.R. Davis Yard." from http://www.up.com/aboutup/facilities/davis/index.htm.

USC. "BNSF Argentine Yard." from http://hydra.usc.edu/scehsc/web/resources/Map/Railyards/Argentine/Overview.htm.

USC. "BNSF Barstow Yard." from http://hydra.usc.edu/scehsc/web/resources/Map/Railyards/Barstow/Overview.htm.

USC. "BNSF Galesburg Yard." from http://hydra.usc.edu/scehsc/web/resources/Map/Railyards/galesburg/Overview.htm.

USC. "CSX Avon Yard." from http://hydra.usc.edu/scehsc/web/resources/Map/Railyards/Avon/Overview.htm.

USC. "NS Conway Yard." from http://hydra.usc.edu/scehsc/web/resources/Map/Railyards/Conway/Overview.htm.

Wikipedia. "CSX Cumberland Yard." from https://en.wikipedia.org/wiki/Cumberland_Terminal_Subdivision#Yard_and_shop_facilities.

Wikipedia. "CSX Selkirk Yard." from https://en.wikipedia.org/wiki/Selkirk_Yard

Wikipedia. "NS Enola Yard." from https://en.wikipedia.org/wiki/Enola_Yard.

Wikipedia. "NS Linwood Yard." from https://en.wikipedia.org/wiki/Linwood_Yard.

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