TRANSPORTATION SIMULATION ONTIME IN iGRAFX® SOFTWARE

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ABSTRACT

Approximately 1.6 million cubic yards of wastes must be transported from the East Tennessee Technology Park (ETTP), Oak Ridge, Tennessee, to final disposal to meet contractual requirements of Bechtel Jacobs Company (BJC)’s Accelerated Closure Contract. The majority of all waste shipments occur during the final two years of this contract. BJC, The Department of Energy's (DOE) environmental clean-up contractor in Oak Ridge, TN, developed a simulation project to design an optimized shipping system that integrates adequate transportation, security concerns, logistical constraints, individual waste generators' requirements, disposal facilities' criteria, and corporate interests. The simulation, in iGrafx® software, is called *OnTime*. The logic, the figures of merit, the validation, and the recommendations based upon *OnTime* are discussed in this paper.

The potential complications simulated by *OnTime* include the effects that maximizing the volume per shipment, spacing evenly the departures of shipments, routing through public traffic, and ensuring security have on transportation safety, time efficiencies, and minimal costs.

OnTime shows that by maximizing the volume per shipment, BJC can minimize the number of trucks used, the number of trucks processed at the disposal sites, the number of trucks that must process back into the fenced area, and the number of trucks that must receive radiological surveys. Furthermore, by constructing a haul road, the risk of traffic accidents is reduced. *OnTime* also calculates the time wasted when shipments fail to adhere to the contract’s scheduling requirements. In simulating these efficiencies, *OnTime* can determine ways to save up to a net value of $10M through a combination of direct savings and cost avoidance.

INTRODUCTION

In order to meet its contractual obligations, BJC will generate, transport, and dispose of approximately 1.6 million cubic yards of remedial action (RA) and Decontamination and Decommission (D&D) wastes between April 2005 and September 2008. During the peak cleanup periods in FY 2006 through 2008, the potential for significant vehicle traffic exists. As a result, bottlenecks can occur at entrance gates, at transportation intersections, and at disposal facilities, to name a few. Waste generation rates from multiple Department of Energy (DOE) prime contractors, various landfill operations, transportation routing and sequencing from a single provider for multiple projects, containerization and truck selection, security issues, process integration and optimization, and costs require studies for optimization in the *OnTime.*

The purpose of *OnTime* is to identify potential queuing delays and their improvements that will achieve a balance between vehicles departing and vehicles arriving at any point in time.

The primary metric is the number of trucks and the amount of time the trucks must spend waiting in line in any queue. Not only is the time waiting a monetary loss, but also significant build-up of heavy equipment in an area of considerable pedestrian traffic is a safety hazard. Further savings are anticipated from the reduction of cycle time per shipment achieved by the designed process.

Process Description

Between 2003 and 2008, an anticipated 1.6 million cubic yards of waste will be generated during the Accelerated Cleanup Project (ACP) that encompasses 112 subprojects generating waste, fifteen of which make up 95% of the total waste volume. For all of the waste, there are eleven disposal outlets, two of which handle 96% of the waste volume. Seventy-nine percent of the waste requiring transportation for disposal is located at the East Tennessee Technology Park (ETTP) from multiple DOE prime contractors, with the remaining waste being generated at the Y-12 National Nuclear Security Administration, the Oak Ridge National Laboratory, Oak Ridge, TN, or Knoxville, TN. The estimated total number of shipments from all sources steadily increases from Fiscal Year (FY) 04 until FY07, with a decrease in FY08.

Between Apr 2005 and Sep 2008, approximately twelve percent of the waste volume will have security issues. Approximately 44% of the wastes are soil, with the remainder being debris. The soil to debris ratio is important for compaction requirements at the contaminated landfill. Approximately 30% of the wastes are not contaminated, with the balance having any combination of RCRA, TSCA, or radioactive contamination. The team narrowed the focus of the project first to the fifteen subprojects comprising 95% of the total volume, and then further narrowed the focus to the two destinations to which 96% of the waste will be traveling. This disposal network is shown in Figure 1.

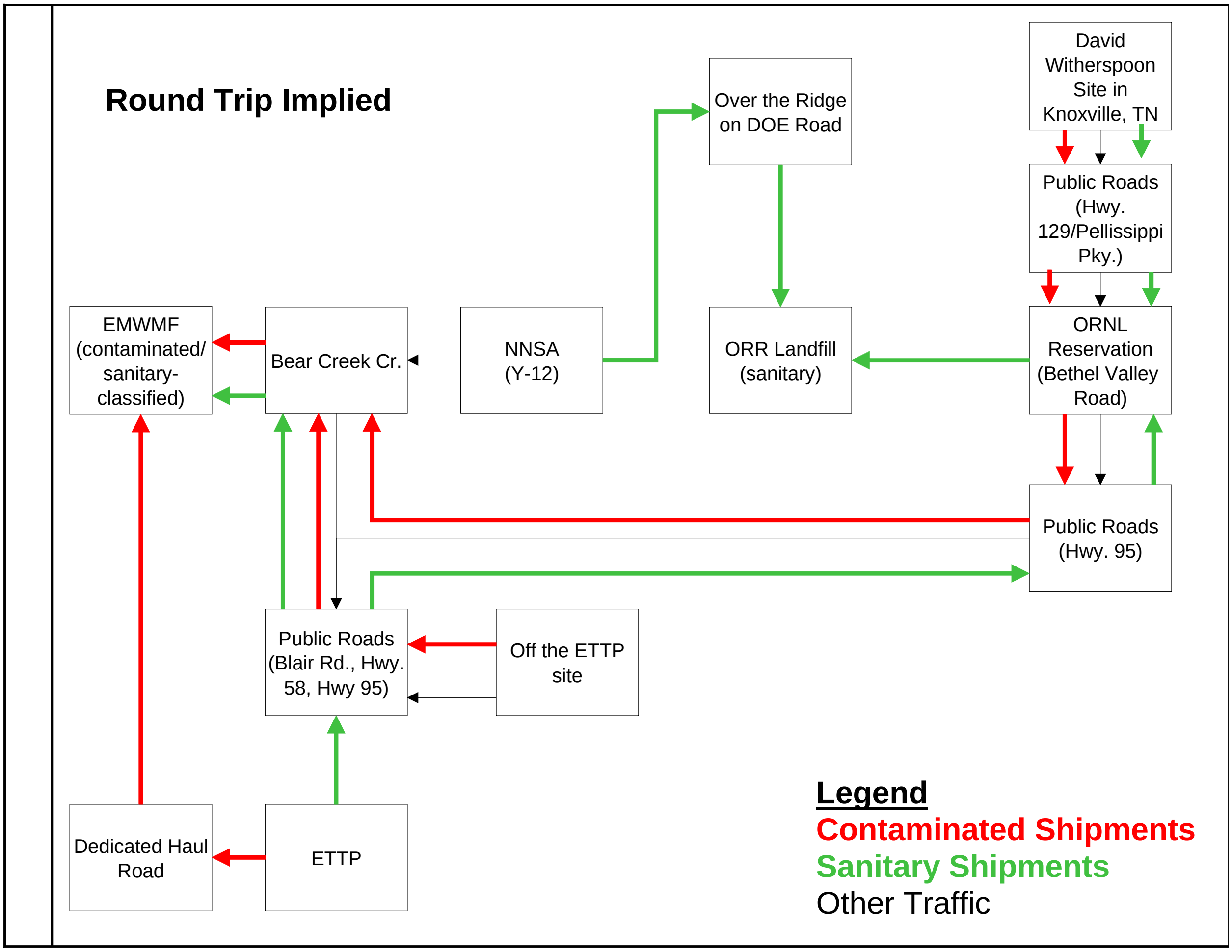


Fig. 1. Disposal network

Determining bottlenecks in a system is an implementation of Little's Queuing Theory (LQT). Consequently, LQT was chosen as the primary metric for *OnTime*. In other words, by determining the number of trucks in any queue (at egress points, the facility entrance gates on return trips, the disposal sites, or traffic intersections), the project could determine bottlenecks in the system. LQT states that the ratio of a vehicle approaching a point of service divided by the vehicle departing the point of service should equal one. If the ratio is less than one, then resources are underutilized. If the ratio is greater than one, there are bottlenecks in the system.

OnTime's secondary metric ensures that the improvements made to ensure the success of the primary metric are not achieved at the expense of another factor in the process. In the case of BJC's transportation, the secondary metric is the costs associated with any improvements identified by *OnTime*.

DESIGNING *ONTIME*

Designing *OnTime* integrated the queuing theory, shipment attributes, the specified routes, the ACP schedule, and stakeholder issues.

Queuing Theory

Queuing theory involves the mathematical study of “queues,” or waiting lines. The formation of waiting lines is, of course, a common phenomenon, which occurs whenever the current demand for a service exceeds the current capacity to provide that service.[a] The operating characteristics of queuing systems are based on an exponential distribution. There are five properties of this exponential distribution.

Exponential Distribution Property #1

The time spent waiting in a queue is strictly a decreasing function of the elapsed time for the next vehicle to enter the queue. From Figure 2, using vehicles approaching a portal as an example, the shorter the elapsed time between a vehicle entering a queue and the longer the service time, an exponential increase in wait time for each vehicle occurs.

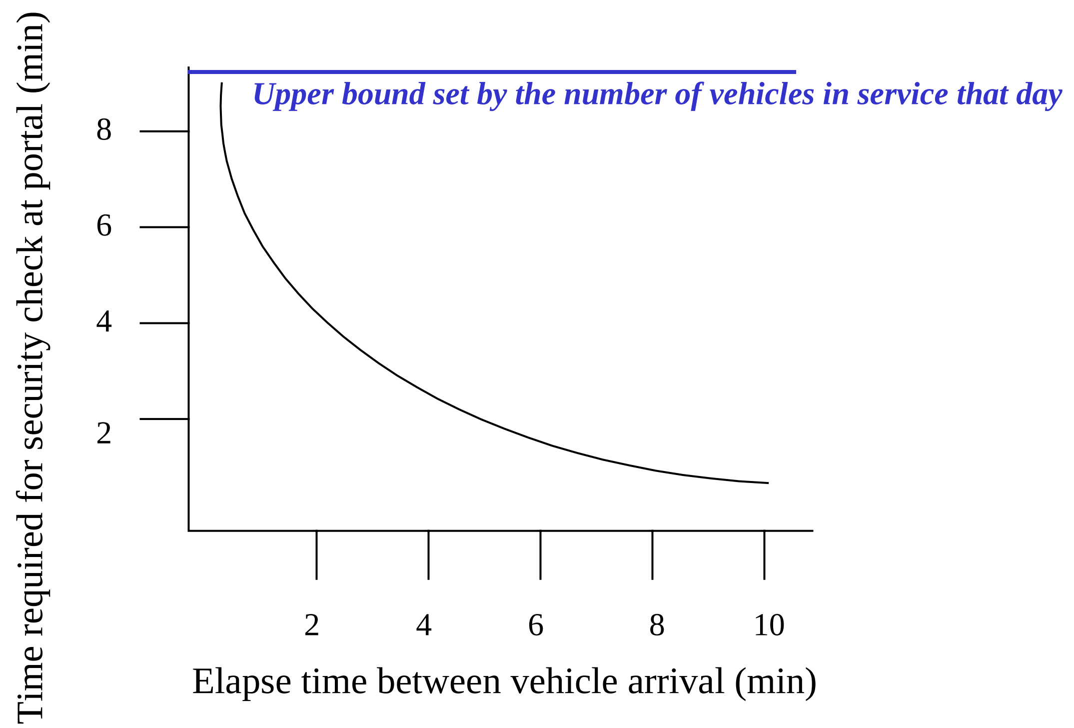


Fig. 2. Exponential distribution of queues

Exponential Distribution Property #2

The second property is called “lack of memory”. In other words, the time until the next vehicle arrives at the portal for a security check is completely uninfluenced by when the first or the last vehicle arrived in the queue.

[a] Hiller, F. S. and Lieberman, G. J., *Operations Research,* 2nd edition, 1974, pg. 379.

Exponential Distribution Property #3
The minimum of several independent exponential random variables has an exponential distribution.

Given that each random variable T has an exponential probability of occurring for any time greater than or equal to 0 of:

$$P\{T > t\} = e^{-\alpha t} \qquad \text{(Eq. 1)}$$

Then several independent variables taken together have a probability of occurring per:

$$P\{T_1 > t\}P\{T_2 > t\}...P\{T_n > t\} = ...e^{-a_1 t}e^{-a_2 t}...e^{-a_n t} \qquad \text{(Eq. 2)}$$

If each variable T is taken as a minimum of that function and if U is taken as the probability of all T variables at a minimum, then it follows that:

$$P\{U > t\} = ...e^{-(a_1+\alpha_2+...+\alpha_n)t} = e^{-\sum_{i=1}^{n}\alpha_i t} \qquad \text{(Eq. 3)}$$

Therefore the probability of U, the minimum of several independent exponential variables, has an exponential distribution as well.

This property has some implications for interarrival times in queuing models. In particular, suppose that there are several (n) different types of trucks, but the interarrival times for each type have an exponential distribution. By property #2, the remaining time from any specified instant until the next arrival of the same type of truck would have this same exponential distribution. Therefore, the remaining time measured from the instant a vehicle of any type arrives has an exponential distribution of the following function:

$$VehiclesInQueue = \exp\left\{-\sum_{i=1}^{n} InterarrivalTimesOfVehicles_i\right\} \qquad \text{(Eq. 4)}$$

where n = different types of trucks, and i = interarrival time.

Exponential Distribution Property #4
Suppose that the elapsed time between Truck 1 and Truck 2 arriving at a security portal has an exponential distribution with parameter α. Property 4 states that the number of times this scenario occurs over a specified length of time is a Poisson distribution with parameter αt. This property provides useful information about service completions.

Exponential Distribution Property #5
For all positive values of t, the probability that exactly n vehicles will be in the queue can be approximated by $\alpha\Delta t$ for small Δt. This property provides a simplification for the other queuing theory mathematics.

Programming Queuing Theory into iGrafx® Software

iGrafx® software allows a simulation to start on a specific date by programming the date into the Run Setup dialog box and using elapse time from that specified date to start various events. *OnTime* starts on 01 Apr 04. iGrafx® then runs in absolute time, based in seconds. Each waste stream has an activity box that allows its various attributes to be programmed into it, such as its final destination, the point of egress, the material type, the project generating the waste, the security required, the waste type, and which route the shipment should take.

In addition to the attributes, the activity box also has a tab for linking that step to an iGrafx® generator. An iGrafx® generator is one of two places where the queuing theory is programmed in the simulation. Each waste stream has its waste generation forecast (WGF) programmed by Fiscal Year quarter inside the iGrafx® generator, such as the start and stop dates, the quantity of waste per cubic yard, and the number of shipments that will be required per hour based on 20 cubic yards per shipment.

The next place where Queuing Theory is programmed is in the Portal Activity Block. Each Portal had its own attributes as well, such as when a shipment arrived at the Portal, and when the shipment started its security entrance procedure. iGrafx® measures the time a vehicle spends in a queue by the difference in time between the "Enter" activity and the "Pre-Task" activity. Each Portal is given variables names, such as Portal5Enter, Portal5Leave, and Portal5QueueTime. Recalling that an iGrafx® simulation is based on absolute elapsed time in seconds from the designated start point (in this case 01 Apr 04 at 8:00 a.m.), each shipment takes on the values of the time it encountered a portal. For example, Portal 5 is programmed to determine the time each shipment spends waiting in the queue be the following equation:

Portal5QueueTime = Portal5Leave – Portal5Enter (Eq. 6)

There are two functions that significantly affect how long a vehicle is in the queue at a Portal, namely, how long the entrance process takes (task time) and how many vehicles can have a entrance process simultaneously (capacity). Different gates have different processing times. Because these gates are one-way, the capacity is considered to be "1", meaning that only one vehicle at a time can receive entrance processing.

The heart of the simulation *OnTime* lies in a function called "logged transactions." This function shows each vehicle with all its attributes and queue time in a spreadsheet. *OnTime's* logged transactions for Portal 5 on 18 June 2007, is considered as an example. This date is Day 1,173 in the simulation, and 1,360 cubic yards of waste needs to be transported through Portal 5 to disposal. The contaminated disposal site is scheduled for a 16-hour day on that date, which, for programming convenience, is from 8 a.m. until midnight. The vehicles are assumed to be carrying 20 cubic yards, and the first trucks arrive at EMWMF at 8:00 a.m., spend 45 minutes, and drive back in 20 minutes to arrive at Portal 5 at approximately 9:20 a.m. The assumption is that each vehicle in the queue has carried 20 cubic yards to disposal. The total time vehicles spend waiting in the queue at Portal 5 on 18 June 2007 is 169 minutes, provided that each shipment has 20 cubic yards in it, which implies that 68 shipments must be made.

The simulation was then statistically validated four different ways: (a) by time, as per the Waste Generation Forecast (WGF), (b) by total shipments leaving all egresses, (c) by total shipments going to EMWMF, and (d) by total shipments going to the ORR Landfill.

- The validation by time has a Test for Equal Variance p value = 0.963, and a Paired T-Test p value = 0.206. Both the WGF and the simulation data are normally distributed when segmented by shipments per quarter (N = 12). This test result validates statistically that the simulation model delivers the correct quantity of shipments in the correct time frame.
- Data used for the validation by total trucks leaving all egresses were non-normal when segmented by destination. ANOVA Levene's test for equal variances had a p value = 0.846. Kruskal-Wallis non-parametric test p value = 0.956 (N = 54). This test result validates statistically that the trucks leaving a particular project went to the correct destination along the desired route.
- Data used for the validation by total shipments going to the sanitary landfill were non-normal when segmented by destination. ANOVA Levene's test for equal variances has a p value = 0.994. Kruskal-Wallis non-parametric test p-value had a p value = 0.825 (N = 54). This test result validates statistically that the ORR Landfill received the correct quantity of shipments in the correct time frame.
- Data used for the validation by total shipments going to the contaminated landfill were non-normal data when segmented by destination. ANOVA Levene's test for equal variances has a p value = 0.656. Kruskal-Wallis non-parametric test p-value has a p value = 0.507 (N = 54). This test result validates statistically that the EMWMF received the correct quantity of shipments in the correct time frame.

OnTime statistically validates against the WGF. This means that the simulation accurately represents BJC's waste by subproject, by waste type, by material type, by security, by planned disposition periods, and by final disposition.

As per the Design Phase requirements, the following output was generated:

- The time spent waiting at any gate, and subsequently the number of trucks in queue at any time;
- The number of shipments on a monthly basis to the contaminated and sanitary landfills;
- The soil to debris ratio at the contaminated landfill;
- The number of classified shipments going to the contaminated and sanitary landfills,
- Accident scenarios based on traffic patterns,
- The effect that randomness has on queues at the portals, and
- The impact on the Oak Ridge National Laboratory (ORNL) and the National Nuclear Security Administration (NNSA) facilities.

Queuing and Wait Time

The haul road is designed to connect to portals 5, 5A, and 6, of ETTP, run parallel to Blair Road, cross Highway 58 with a bridge, run parallel to Bear Creek Road, cross Highway 95 with a bridge, run parallel to Bear Creek Road, and enter the contaminated landfill. Once the haul road is operational, all waste originating at ETTP will use it. The sanitary waste will travel on the haul road until it merges with the Closure and Post Closure Actions (CAPCA) road, at which point the sanitary shipments will cross Bear Creek Road, go over Chestnut Ridge on Reeves Road, turn east on Bethel Valley Rd., then up Clear Spring Rd to the sanitary landfill. The anticipated distribution of shipments is:

- Main Plant D&D, Zone 1 (excluding Blair Road Quarry) will use Portal 6;
- Zone 2, Powerhouse Road, and the K-29/31/33 D&D will use Portal 5A[b]; and
- The K-25/K-27 D&D will use Portal 5.

The haul road is expected to be operational July 2005.

The simulation assumed that portals would operate the same hours as EMWMF as well as an hour earlier and an hour later. The following dates are when EMWMF will operate two consecutive shifts, according to *The Bechtel Jacobs Company, LLC, Accelerated Closure Project Waste Transportation Plan*, DOE/OR/01-2126:

- 01 Aug 05 – 10 Oct 05
- 4 Sep 6 – 25 Sep 06
- 06 Nov 06 – 26 Nov 07
- 4 Feb 08 – 28 Apr 08

The simulation was used to determine the traffic on the haul road. Table II shows that the maximum number of vehicles on the haul road is 43 per hour. As the haul road is 8 miles long, the maximum is less than 6 vehicles per mile at any given time, so no bottleneck is anticipated on the haul road.

Table II. Haul Road Vehicle Traffic*

	Haul Road Round Trip Shipments/Day	Haul Road Single Passes/Day	Haul Road Single Passes/Hour
Distribution	non-normal	non-normal	non-normal
Minimum	1	2	0
Median	77	154	11
Maximum	170	340	43

*Assumes 20 cubic yards per shipment

All of the gates were checked for total wait time, and Table III shows the total hours that vehicles hauling waste will wait on the return trip from the disposal facility.

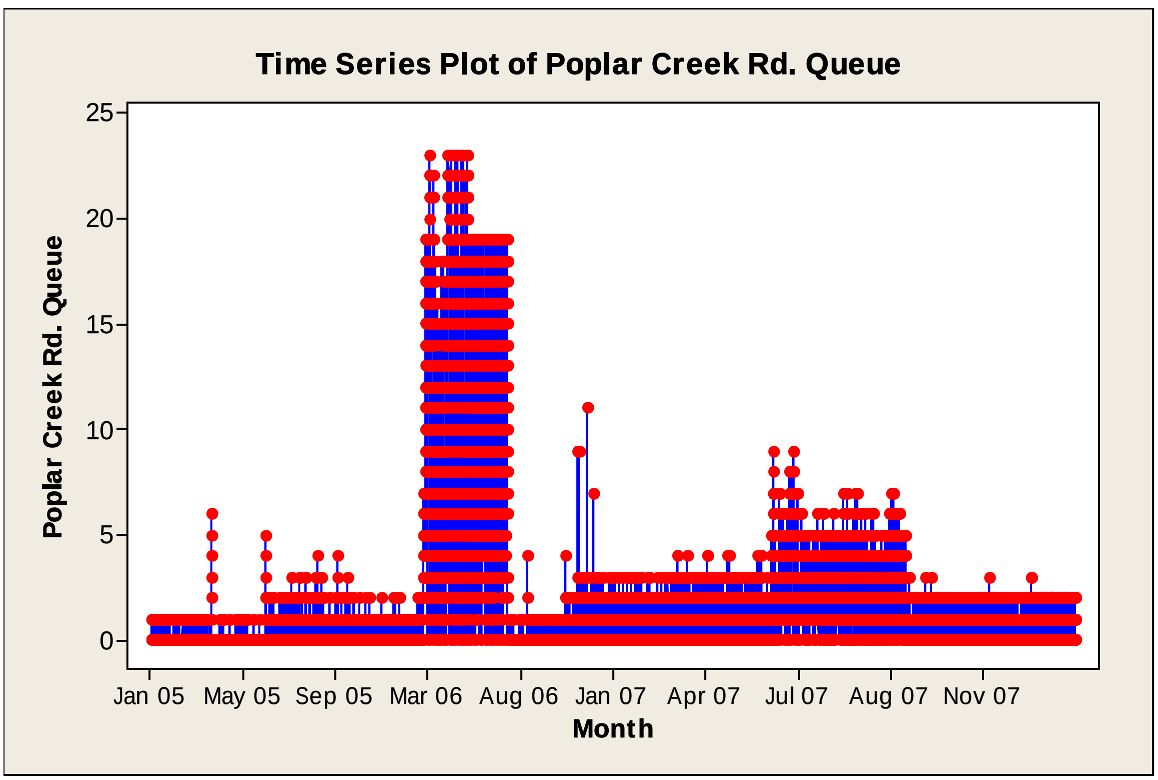
[b] The K-31/33 project may decide in the future to go out Portal 8 to a spur to the haul road at Portal 3. Some of the Main Plant D&D may use this spur as well instead of Portal 6. As of Dec 2004, the spur to the haul road has not been approved.

Table III. Base Case for Portal Vehicle Traffic*

Portal	Total Vehicle Count (Jul 05 - Sep 08)	Median Wait Time per Vehicle (min)	Maximum Wait Time per Vehicle (min)	Total Wait Time for All Vehicles (hr) (Jul 05 - Sep 08)
5	23,395	1	25	1,156
5A	15,182	2	249	11,214
Poplar Creek Road (Portals 5 + 5A)	38,577	1	249	12,370
6	17,371	0	84	268
Totals	55,948			12,638

*Assumes 20 cubic yards per shipment

Because of the significant wait time Portals 5 and 5A potentially have, Poplar Creek Road was further analyzed for queue build-up. Figure 13 shows that the maximum number of vehicles in line at any given time on Poplar Creek Road is 23. During weeks 99 - 122 of the simulation (March 2006 to August 2006), 6,533 shipments of waste will pass through Portal, and 177 vehicles will pass through Portal 5. The total wait time during this period is 11,095 hours for Portal 5A and 15 minutes at Portal 5. This is during a time period when there is a single shift at the portals. The major queuing opportunity is between weeks 103 and 115 of the simulation (April 2006 and June 2006).



*Assumes 20 cubic yards per shipment

Fig. 3. Poplar Creek Road queue (Portals 5 + 5A)*

Shipments to the Contaminated and the Sanitary Landfills

The contaminated and sanitary landfills need to know how many shipments will be arriving on a monthly basis so that adequate resources will be available. *OnTime* calculated the average number of shipments per month is 1,118 to the contaminated landfill. The minimum occurs during September 2008 with 26 shipments, and the maximum occurs during August 2007 with 1,893 shipments.

OnTime calculated the median number of shipments per month is 485 to the sanitary landfill. The minimum occurs during September 2008 with 22 shipments, and the maximum occurs during May 2006.

Accident Scenarios

The probability of various traffic accidents occurring based on 1,000,000 vehicles entering a particular type of intersection were determined from statistical tools provided by the Tennessee Department of Transportation. Intersection types were "spot in the road", such as a driveway merging into another road, a two-lane highway, a divided highway, and a four-lane highway. To support these calculations, eighteen days of traffic pattern data were collected. Table IV shows the traffic patterns for potential public highway routes.

Table IV. Public Highway Traffic Patterns

	South/West-Bound Maximum		North/East-Bound Maximum		Daily Total
Location	Vehicles/Hr	Time	Vehicles/Hr.	Time	
Blair Rd.	295	6:00	209	15:00	3,148
Highway 58	816	15:00	926	6:00	14,328
Highway 95	519	6:00	382	15:00	6,625
Cloverleaf	768	6:00	621	15:00	7,260
Bear Creek Rd. @ ETTP	90	17:00	109	6:00	694
Bear Creek Rd. @ Hwy. 95	54	6:00	43	17:00	505
Bear Creek Rd. @ NNSA	478	15:00	629	6:00	2,932
East End Bethel Valley Rd.	1,083	6:00	775	15:00	8,223
West End Bethel Valley Rd.	492	15:00	758	6:00	4,526

A summary of the minimum statistical probability of an accident at a particular intersection can be easily programmed. For the time period between April 2004 and September 2008, the following accidents may statistically occur:

- one accident at Blair Road and Poplar Creek Road;
- three accidents at Highway 58 and Blair Rd.;
- one accident at Highway 95 and Bear Creek Rd.; and
- one accident at Highway 95 and Bethel Valley Rd..

The Impact on the ORNL and NNSA

The vehicles hauling waste from ETTP must travel on DOE property that is part of ORNL and NNSA. The maximum number of shipments on Bethel Valley Road, which is on ORNL property, is 45 in one day during April 2006. The maximum number of shipments on Bear Creek Road, which is on NNSA property, is 128 in one day during March 2006.

The Impact of Partially Filled Trucks

The capacity of a truck is regulated by weight, not volume. Trucks must still maintain a gross weight of less than 80,000 lbs. Thus, filling a truck to capacity is actually a matter of utilizing bed volume, up to the weight limit. It is conceivable that shipments of concrete debris and non-mangled steel could hit the weight limit before reaching 20 cubic yards. For instance, if a truck has a tare weight of 35,000, a 20 cubic yard load weighing 45,000 lbs. yields a density of 2,250 lbs./cubic yards, if comprised of loose dirt.

It is in BJC's best interest to fill trucks to the fullest capacity that the weight limits will allow. The impact of partially filling trucks was simulated by programming the shipments for 12.5 cubic yards instead of 20 cubic yards. Data from the contaminated landfill indicate that traditionally shipments in 22 - 24 cubic yard capacity trucks have between 10 to 15 cubic yards of material in them. Team process knowledge doesn't indicate that BJC has been pushing up against the limit. While the increase in the number of vehicles is relatively linear, the queue time is not. An example of this is where Day 1,173 of the simulation (18 Jun 2007) is re-evaluated for shipments with only 12.5 cubic yards in each shipment coming out Portal 5. The same quantity of waste is shipped (1,380 cubic yards) using 109 shipments. The original evaluation in with 20 cubic yards per shipment and 68 shipments for 1,380 cubic yards had a total wait time of 168 minutes. *OnTime* shows that the additional 41 shipments require a total wait time of 6,572 minutes, about a factor of 38 times more than just 68 shipments in a day.

The total hours spent waiting increases from 12,638 hours (6.8 FTE) to 85,304 hours (~46 FTE). This is time lost not only at the gate but at the generating projects as well. Furthermore, the increase in trucks waiting in line at the portals is a safety hazard as there is significant pedestrian traffic at each of the portals. From all aspects, it is crucial to fill the trucks to approximately 75% capacity (20 cubic yards in a 26 cubic yard capacity truck).

Table VI. The Impact of Partially Filled Trucks

Partially Full Shipments				
Portal	Total Vehicle Count (Jul 05 - Sep 08)	% Increase Vehicles Over Base Case	Total Wait Time for All Vehicles (hr)	% Increase Wait Time @ Portals Over Base Case
5	37,440	160%	33,826	2926%
5A	19,290	160%	50,566	51077%
6	30,322	160%	912	340%
Total	87,051		85,304	674%

Design of Experiments

A Design of Experiments (DoE) was performed to determine which improvements have the greatest impact. The primary metric is the number of trucks in queue, which can be translated into hours waiting. 7 shows the hours waiting without the improvements of (A) the haul road construction, (B) the trucks filled to 75% capacity, and (C) random schedules eliminated.

Table VII. DoE Input for Primary Metric

Factor	Variable	High Value (hr)	Low Value (hr)
A	haul road	19940	0
B	full trucks	72667	0
C	random schedules	1157	0

Figure 3 shows that filling trucks to 75% capacity has the greatest impact on cycle time.

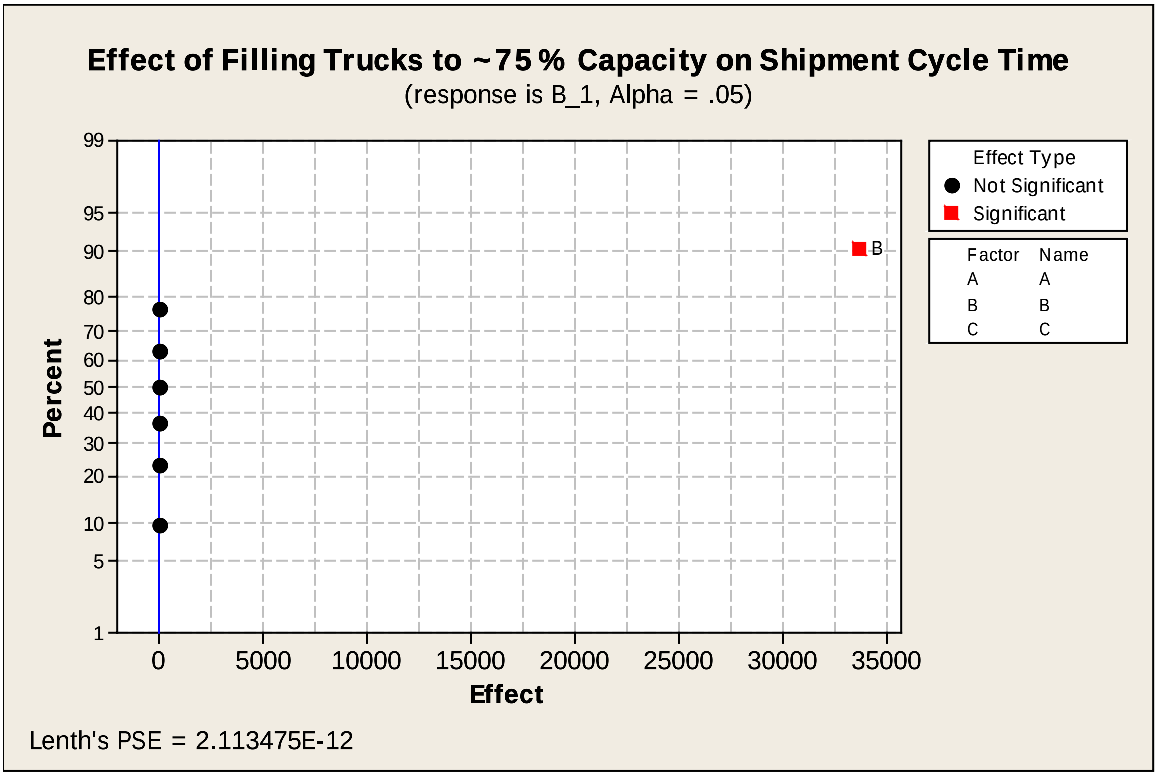


Fig. 3. Impact of filling shipments to ~ 75% capacity on cycle time

The secondary metric is cost. Table 8 shows the cost savings with the improvements of (A) the haul road construction, (B) the trucks filled to 75% capacity, and (C) random schedules eliminated.

Table VIII. DoE Input for Secondary Metric

Factor	Variable	High Value	Low Value
A	haul road	$0.00	-$4,927,233.00
B	full trucks	$15,204,325.00	$0.00
C	random schedules	$400,189.00	$0.00

Filling trucks to 20 cu yds per shipment has the greatest impact on cost savings by far, as seen in Figure 4.

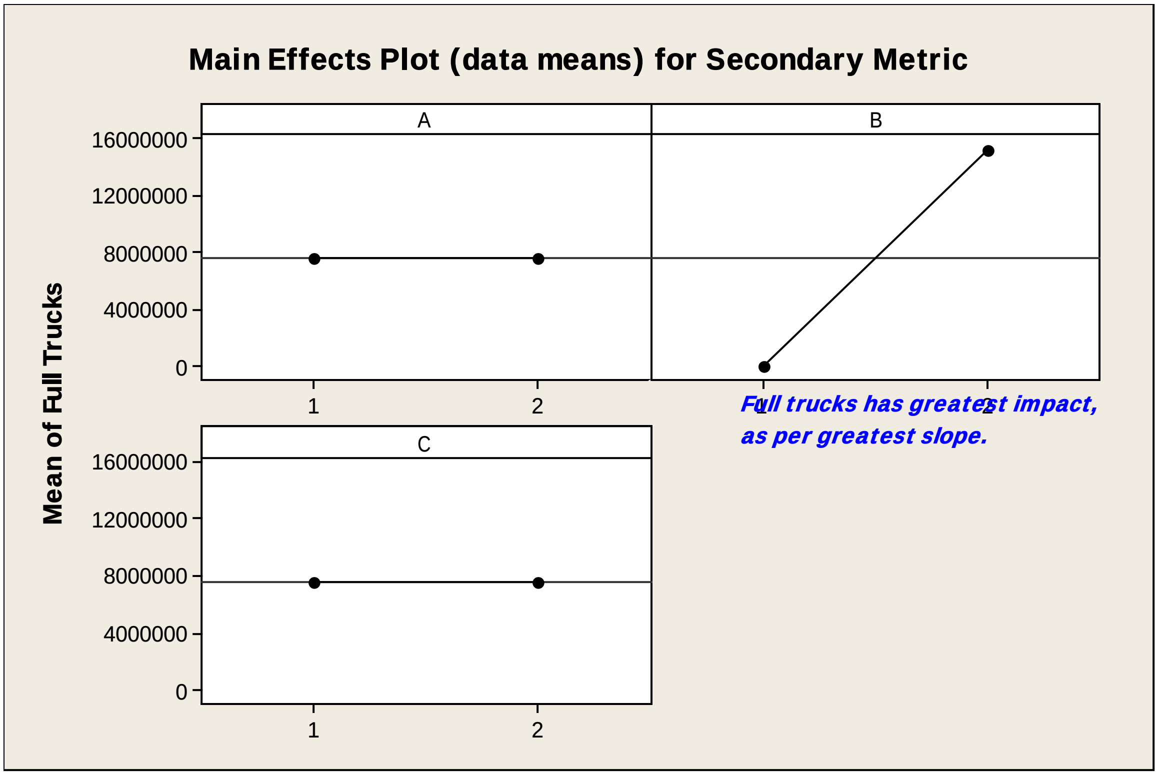


Fig. 4. Haul Road significant to cost savings

Simulation Recommendations

Filling the trucks to 20 cubic yards per 26 cubic yard capacity, building a dedicated haul road, enforcing strict adherence to disposal facility weigh-in times, and incorporating strict adherence to schedules in the transportation subcontract are the key recommendations from *OnTime*.