Transportation Modeling
An Introduction

KHNP Training Program
Module #: Transportation Module 13

January 15, 2008

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SAND 2008-1095P

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for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Mathematical Modeling Activities

- Research, design, develop, and implement optimization and simulation-based technology across broad set of application domains
  - Logistics Modeling
  - Critical Infrastructures
  - Transportation
  - Process Modeling
- Network analysis incorporates:
  - Physical components and connections
  - Business rules
  - Interdependencies between networks
  - Dynamic nature of system
- Goals:
  - Improve decision making
  - Identify vulnerabilities & disruption impacts
  - Determine efficient use of scarce resources
  - Incorporation Uncertainty into “What’s Best” analysis

Mathematical Arena

- Mathematical programming & simulation capability
  - Linear Programs (LPs)
  - Mixed Integer Programs (MIPs)
  - Non-linear Programs
  - Discrete-event simulation
  - Heuristics
  - Continuous-flow simulation
- Exploiting the benefits of optimization and simulation
  - Optimization under Uncertainty
  - Stochastic Optimization
  - Experience with combining optimization and simulation in application

Topics

- Section I – What is modeling?
- Section II – Types of mathematical models
- Section III – Transportation of Spent Nuclear Fuel
- Section IV – Simulation Modeling of US Border Crossing

Section I - What is Modeling?

- A model is something which mimics the relevant features of something being studied
- Example:
  - Road Map, geologic map, and a plant collection all mimic different aspects of a part of the earth's surface
- Test of the worth of a model is how well it performs when it is applied to the problem it was designed to handle
- Example: You can not complain if a geologic map does not have a highway marked on it, but this would be a serious deficiency for a road map

Mathematical Models

- An abstract model (or conceptual model) is a theoretical construct that represents something, with a set of variables and a set of logical and quantitative relationships between them.
- A mathematical model is an abstract model that uses mathematical language to describe a system.
- Models which *mimic* reality by using the language of mathematics
- Why mathematics for modeling?
  - We must formulate our ideas precisely so we are less likely to let implicit assumptions slip by
  - We have a concise “language” which encourages manipulation
  - We have a large number of potentially useful theorems available
  - We have high speed computers available for computations

Properties of Models

- A mathematical model is an abstract, simplified, mathematical construct ***related to part of reality*** and ***created for a particular purpose***
- Divide the world into 3 parts
  1. Things whose effects are neglected (neglected/ignored)
  2. Things that affect the model, but whose behavior the model is *not* designed to study (exogenous variables or model input)
  3. Things the model is designed to study (endogenous, output or dependent variables)

Properties of Models

- Divide factors into neglected, input and output are key decisions
- If the wrong things are neglected, the model will be useless
- If too much is taken into consideration, the model will be hopelessly complicated and require large amounts of data
- Often different models are possible for the same situation
- Usually there is no single “best” model
- Not possible to “maximize generality, realism and precision” - Always a trade-off

Building a Model

1. Formulate the Problem: What do you wish to know?
2. Outline the Model: Separate the world into unimportant, exogenous and endogenous, as well as the interrelationships between these
3. Is it Useful? (Not, is it reasonable or accurate?)
4. Test the Model (Are the predictions sufficiently accurate for the defined purpose?)

Example: Population Growth

- Suppose we want to predict how a population will grow numerically over a few generations
- Exogenous variable will be net reproduction rate ***r*** per individual and the size of the population at ***t=0*** represented as ***N(0)***
- Net reproduction rate ***r*** is the birth rate minus the death rate
- Equivalently, ***r*** is the fractional rate of change of the population size
- Model calculates the size of the population ***N(t)***

$$r = \frac{1}{N}\frac{dN}{dt}$$

Example: Population Growth

$$r = \frac{1}{N}\frac{dN}{dt} \longrightarrow N(t) = N(0)e^{rt}$$

- **What do you think about this model?**
- **What happens if r is <0, >0, =0**
- **What step failed in the modeling process?**

Example: Population Growth

- **Growth rate should depend on the size of the population**
- **When the population is large, there is likely to be food shortages**
- **Mathematically this means that *r* should be a function of the population size *r(N)***

$$r(N) = \frac{1}{N}\frac{dN}{dt}$$

- **Now need to specify a function for *r* instead of a single value! More data needed!**

Example : Population Growth

- Suppose *r(N)* starts at some positive value and as the population size (increases), approaches N_0 the rate goes to zero. As the population grows beyond N_0, the rate is negative
- If the initial population is less than N_0,, what will the maximum population size predicted be?
- Populations fluctuate and often overshoot steady state

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Example : Population Growth

- **Our model could allow for overshooting the steady state population by introducing time lags**
- **Suppose there is a constant death rate, but the birth rate is dependent on the population size some number of periods back**

Death Rate

$$\frac{dN}{dt} = -mN(t) + bN(t-p)$$

Birth Rate

Why Study Modeling?

- Why not just experiment with the real world?
- Reduce the need for costly, undesirable or impossible experiments
- Illustrations
  - What is the most efficient way to divide fuel between the stages of a multistage rocket?
  - What would be the effect of a breach in a nuclear reactor?
  - What is the proper staffing level in an emergency room?
- If you are to use mathematical modeling effectively, you must be able to go back and forth between the real world and the world of mathematics/computation

Classifying of Mathematical Models

- Many mathematical models can be classified in several ways:
  - Linear –vs- nonlinear
  - Deterministic –vs- probabilistic (stochastic):
  - Static –vs- dynamic
  - Lumped parameters –vs- distributed parameters

Linear –vs- Nonlinear

- Mathematical models are usually composed by variables, which are abstractions of quantities of interest in the described systems, and operators that act on these variables, which can be algebraic operators, functions, differential operators, etc. If all the operators in a mathematical model present linearity, the resulting mathematical model is defined as linear. A model is considered to be nonlinear otherwise.

Deterministic –vs- Probabilistic (stochastic)

- A deterministic model is one in which every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables. Therefore, deterministic models perform the same way for a given set of initial conditions. Conversely, in a stochastic model, randomness is present, and variable states are not described by unique values, but rather by probability distributions.

Static –vs- Dynamic

- **A static model does not account for the element of time, while a dynamic model does. Dynamic models typically are represented with difference equations or differential equations.**

Lumped –vs- Distributed Parameters

- If the model is homogeneous (consistent state throughout the entire system), the parameters are lumped. If the model is heterogeneous (varying state within the system), then the parameters are distributed. Distributed parameters are typically represented with partial differential equations.

Models and Reality

- Inherent trade-off between theory and computation
- Theory is generally useful for drawing general conclusions from simple models and computers are useful for drawing specific conclusions from complicated models
- Theory is also useful to "check" complicated models

Section II – Types of Mathematical Models

- Numerous modeling techniques exist including:
  - Discrete event simulation
  - Continuous flow simulation (Dynamical Systems)
  - Agent-based simulation
  - Statistical
  - Optimization
  - *Many more…*

- Focus this discussion on Discrete event Simulation and Optimization
  - Pros/Cons

What is a "Simulation Model"?

- Technique for imitating (or simulating) the operation of something
- Descriptive in nature
- Create a model of the system
- Evaluate the model numerically
- If there are random variables in the model then
  - Output from the model is stochastic
  - Estimates of the true characteristics of the system
- Must specify a SINGLE choice for each decision to be made to create an artificial history
- "What if" analysis

What is an "Optimization Model"?

- Mathematical equations which specify the relationship between system elements
  - Variables
  - Constraints
  - Objectives
- Choices to be made are decision variables in the equations
- Solution procedure searches over all the possible values for each variable and produces the best solution
- Optimal solution is the solution which does the best according to the predefined relationship between the variables and the goals identified
- Less descriptive, but more rigorous
- "What's Best" solution

How to Choose?

- Neither is always best – situation dependent
- Both modeling techniques give insight into system behavior
- Situation determines which one to apply
- How to decide:
  - Optimization should be considered first
    - Can equations be written which describe the relationship between system elements?
    - Is the necessary uncertainty represented?
    - Is there a “standard” solution procedure available?
    - If not, can a heuristic be created?
  - If optimization proves infeasible, then simulate
    - Simulations are very flexible
    - Almost “no limit” to what can be represented.

Why Not Always Simulate?

- Simulations are large statistical experiments
  - Lots of data (easy to get overwhelmed)
  - Can be hard to interpret because the outputs are random variables
  - Sometimes hard to determine whether an observation in an artificial history is the result of system interrelationships or randomness
- Lots of scenarios have to be evaluated to cover the whole design space
  - Example: 10 choices to make each with 3 alternatives➔ 60,000 scenarios to consider either explicitly or implicitly
- More difficult to validate and verify

Example

- A construction site requires a minimum of 10,000 cu. meters of sand and gravel mixture. The mixture must contain no less than 5,000 cu. meters of sand and no more than 6,000 cu. meters of gravel.
- Material may be obtained from two sites: 30% of sand and 70% of gravel from site 1 at a delivery cost of $5 per cu meter and 60% sand and 40% gravel from site 2 at a delivery cost of $7 per cu. meter.

- How much should you buy from each site?

Example

x_1: # of cubic meters of mix to purchase from site 1

x_2: # of cubic meters of mix to purchase from site 2

Min $5 x_1 + 7 x_2$

Such that:

$0.3 x_1 + 0.6 x_2 >= 5{,}000$

$0.7 x_1 + 0.4 x_2 <= 6{,}000$

$x_1 + x_2 = 10{,}000$

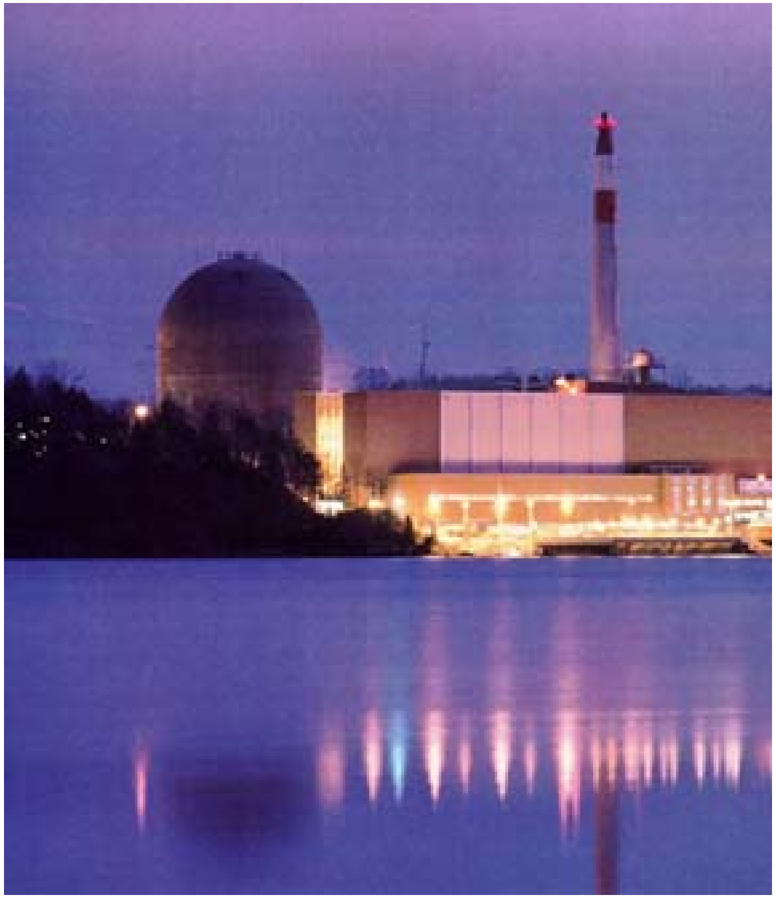
$x_1, x_2 >= 0$

Questions to Consider

- Can simulations and optimizations be combined?
- What are the advantages/disadvantages?

Transportation of Spent Nuclear Fuel to Yucca Mountain

Nuclear Power in the US



- 103 commercial nuclear power reactors
- Longstanding issue of disposing of spent nuclear fuel
- Transport and waste repository planning
- Repository scheduled to open in 2010

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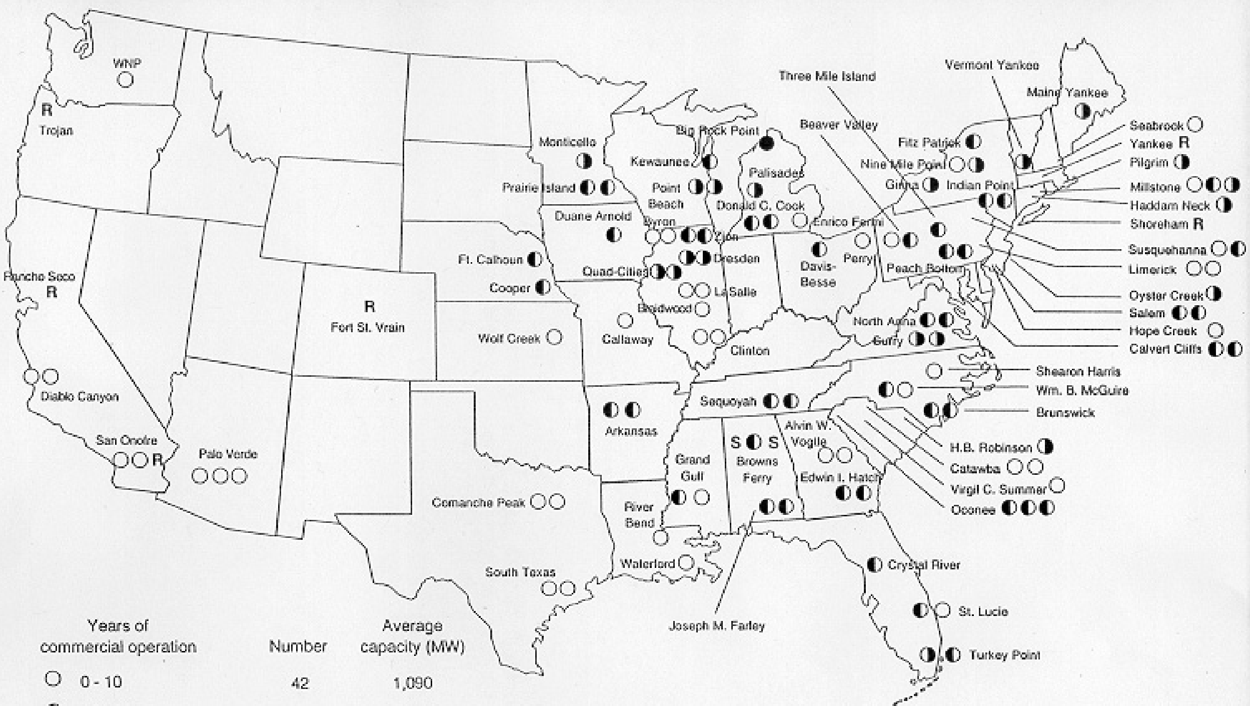
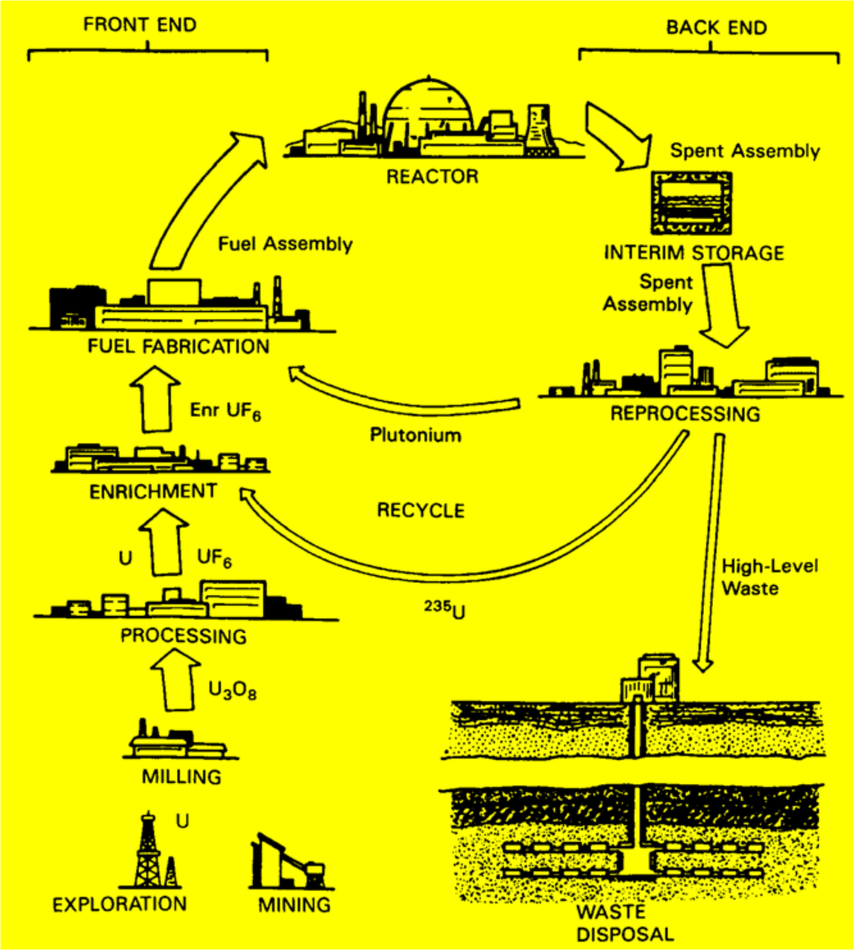
Nuclear Power Plants in the U.S.



Years of commercial operation		Number	Average capacity (MW)
○	0 - 10	42	1,090
◐	10 - 20	44	860
◑	20 - 30	20	660
●	Over 30	1	69
R	Retired since 1988	6	620
S	Shut down under review	2	1,065

SOURCE: Adapted from U.S. Nuclear Regulatory Commission, *Information Digest* (Washington, DC: USNRC, 1992).

Nuclear Fuel Cycle



A Little History

- 1983: Nuclear Waste Policy Act specifies that federal gov't will accept waste starting in 1998
  - DOE starts studying several possible repository sites
  - Utilities start paying $0.001/kWh into waste fund
  - DOE will take ownership of wastes at plant sites and be responsible for transportation
- 1987: Congress limits possible repository sites to one – Yucca Mountain, Nevada

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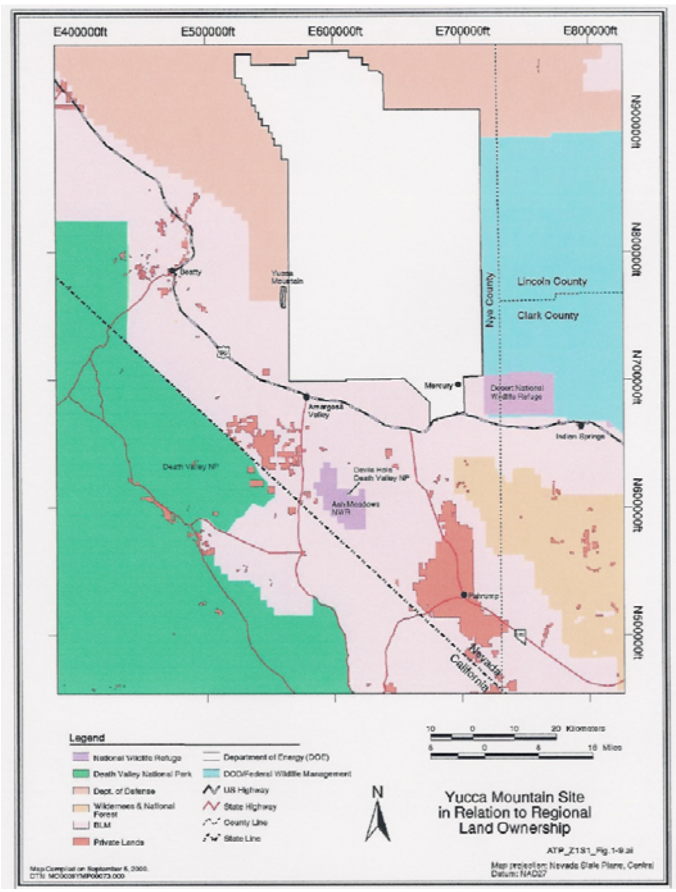
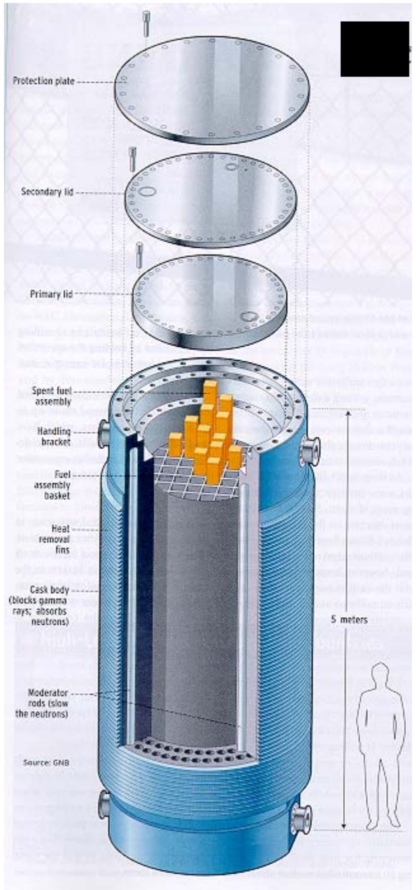
Yucca Mountain



- Site is about 100 miles northwest of Las Vegas and Northeast of Death Valley National Park
- Near the edge of Nellis AFB and the Nevada Test Site

Storage / Transportation Casks

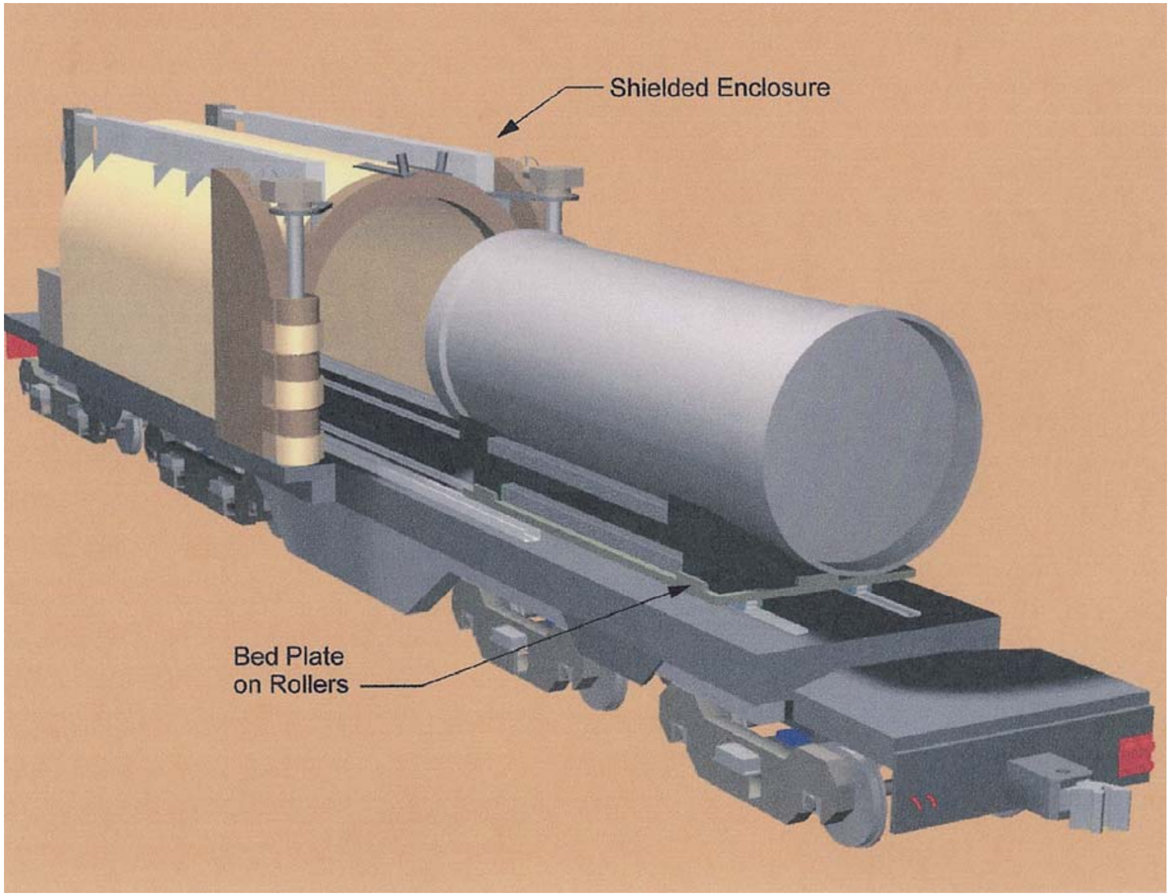


- Approximately 5.6 meters high
- Rail and Truck Models (several of each, from different vendors)
- Rail Cask:
  Loaded weight $\approx$ 100,000 kg
  Holds 24-68 spent fuel assemblies
- Truck Cask:
  Loaded weight $\approx$ 25,000 kg
  Holds 1-9 assemblies

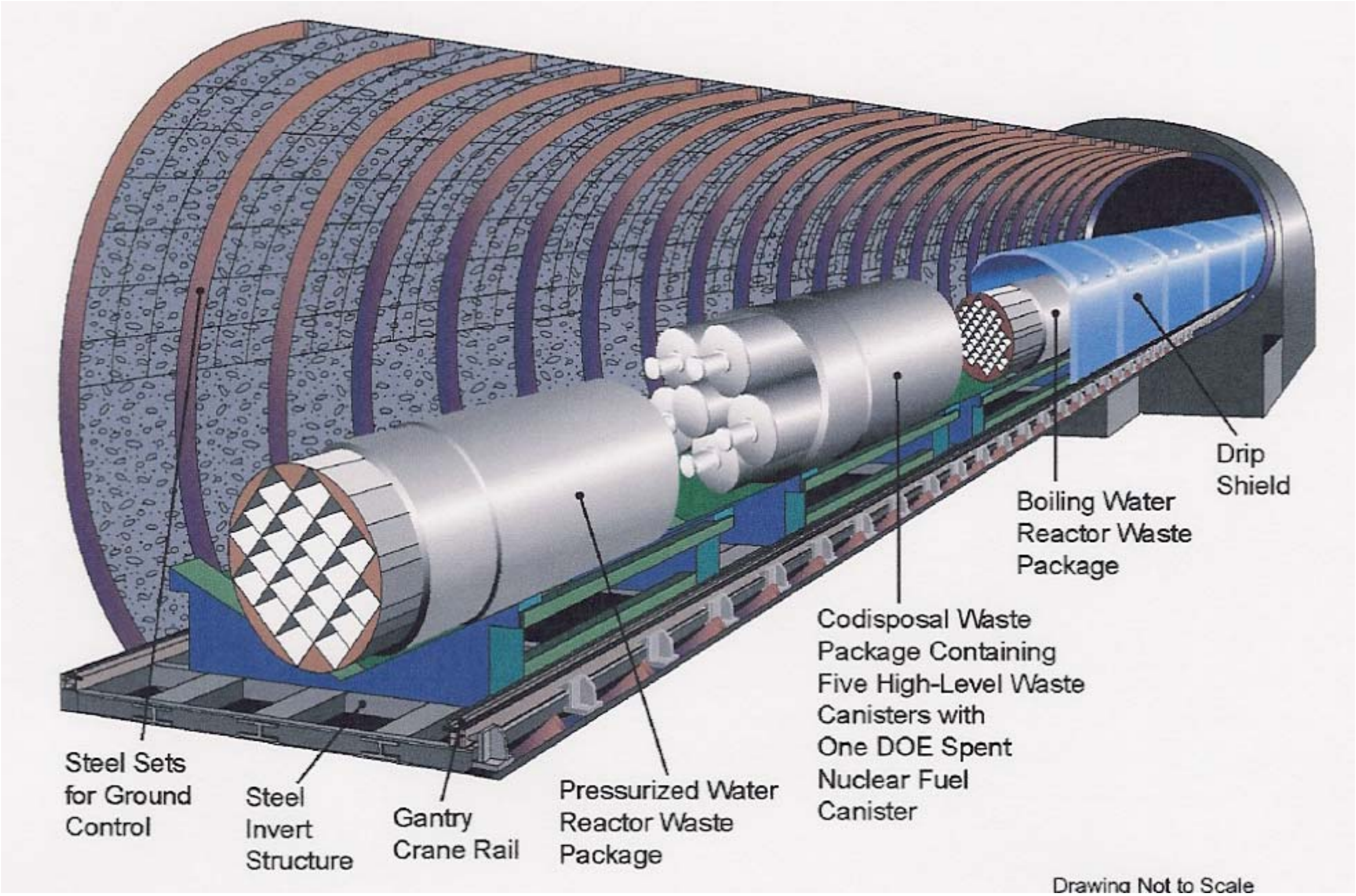
Storage / Transportation Casks

Dry Cask Storage On-Site

Emplacement Transporters



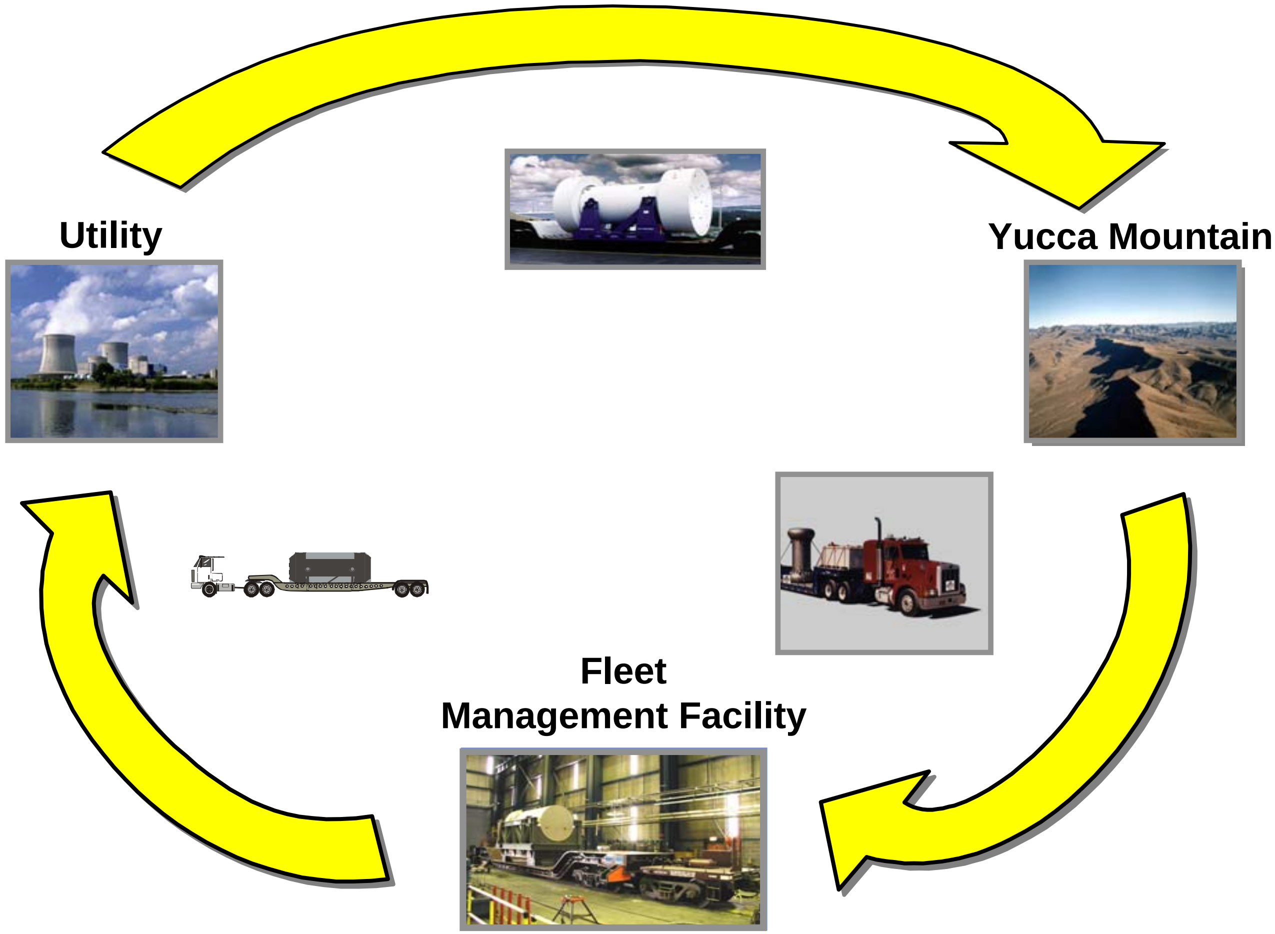
Waste Packages in Drift



Modeling Goals

- Overall – Phased Approach
  - Create a suite of decision support tools to assist the OCRWM Office of National Transportation (ONT) with critical decision making
- Phase I: Investment Planning Model (IPM)
  - Develop a long range planning tool in support of ONT's transportation resource acquisition process
- Phase II: Operations Planning Model (OOM)
  - Develop a mid-range, operational planning capability focusing on the allocation of acquired resources
- Phase III: Operations Management Model (OMM)
  - Develop an operations management tool focusing on scheduling shipments

Transportation Cycle



Investment Planning Model Approach

Develop an optimization-based modeling tool to help provide a resource investment planning strategy

- **Subject to the constraints:**
  - **Waste Acceptance**
  - **Transportation**
  - **Yucca Mountain**
  - **Security**
- **Resources**
  - **Casks**
  - **Railcars**
  - **Trailers**
- **Time Resolution**
  - **Annual, Semiannual**
- **Analysis Horizon**
  - **Multiple years; decades**
- **Operate the model in 2 modes**
  - **Acquisition**
  - **Evaluation**

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Decision Support

- Acquisition Model
  - A capital acquisition plan for casks, railcars and trailers
    - Supports the projection of system cost
    - Supports the investigation of the terms of purchase for these assets
    - Supports the development of campaign shipping schedules
- Evaluation Model
  - Evaluation of the impact of a particular acquisition strategy
    - Enable the understanding of the risk associated with a given acquisition strategy
    - Support the development of campaign shipping schedules
- Evaluation of the impact of route selection on cask, trailer and railcar needs

Acquisition Model

- Objective: Minimize investment costs
- Constraints:
  - Waste acceptance constraints
    - Cumulative MTHW requirements across all commercial sites
    - Cumulative assembly shipment requirements by utility group by time period
    - Material availabilities for shipment by site
    - No shipment from a site during its outage period
    - Loading time at the shipper site
  - Transportation constraints
    - Acceptable routes and casks which are available for each campaign
    - Asset requirements for each campaign, mode, route and feasible cask combination
    - Cask acquisition limits
    - Cask retirements
  - Yucca Mountain constraints
    - Acceptance rate at Yucca Mountain
    - Turnaround time at Yucca Mountain
    - Maximal average thermal load of casks shipped per period

Evaluation Model

- Objective: Minimize difference between the shipping plan and the cumulative shipping targets
- Constraint:
  - Waste acceptance constraints
    - Material availabilities for shipment by site
    - No shipment from a site during its outage period
    - Loading time at the shipper site
  - Transportation constraints
    - Acceptable routes and casks which are available for each campaign
    - Asset requirements for each campaign, mode, route and feasible cask combination
    - Fixed number and type of casks, railcars and trailer
      - Fixed availabilities by time period for these transportation assets
    - Cask retirements
  - Yucca Mountain constraints
    - Acceptance rate at Yucca Mountain
    - Turnaround time at Yucca Mountain
    - Maximal average thermal load of casks shipped per period

“What-If” Capability

The model is designed to address “what-if” scenarios:

- What is the impact to the resource acquisition plan if a different route between Site A and Yucca Mountain is selected?
- What is the impact to the resource acquisition plan if the turn-around time at Yucca Mountain changes?
- When should DOE begin to procure transportation casks? What kind should be procured? How many this year? Next year? Future years?
- What is the impact of increased security restrictions? Increased time in transit?

All model inputs can be used as “what-if” parameters.

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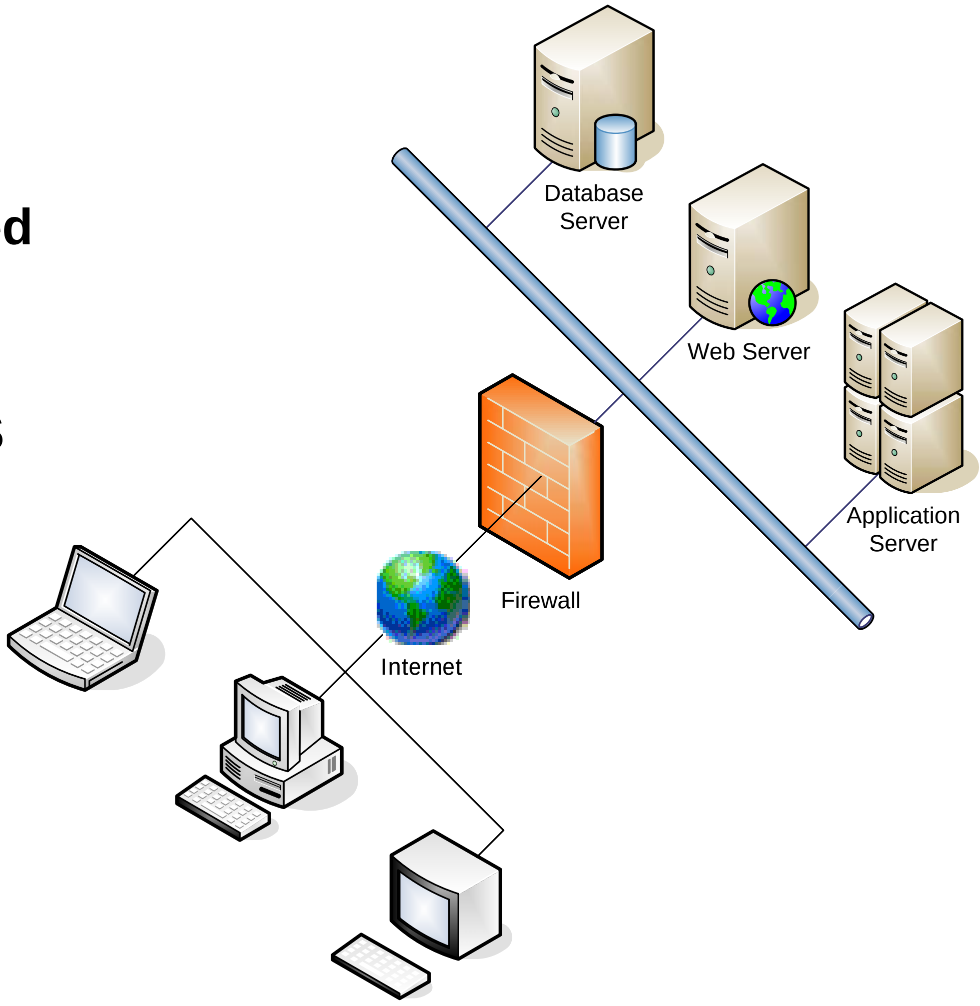
System Architecture

- Access to IPM via Web Browser
- Username & password controlled
- Features of model available based on user privileges
- Data stored in SQLServer DBMS



Scenario 1 - Baseline

Goal: Establish a baseline scenario for comparison

- **Analysis Horizon: 2008-2012**
- **First shipment: 2010**
- **Time Resolution: Annual**
- **Site Loading Days: 3**
- **Yucca Mountain cask turnaround time: 7 days**

Scenario 1 - Baseline

- 61 allocations to the utilities (measured in MTHM)

Year	MTHM
2010	406
2011	596
2012	1191
Total	2193

- 77 sites – Majority are rail sites
- 10 Truck sites
  - Cooper Station
  - Fort Calhoun
  - Ginna
  - Indian Point 1
  - Indian Point 2 & 3
  - Millstone
  - Monticello
  - Palisades
  - Pilgrim
  - St. Lucie

Scenario 1 - Baseline

- 12 Base casks with current certifications
  - Rail
    - NAC-STC (PWR)
    - NAC-UMS (PWR & BWR)
    - HI-Star (PWR & BWR)
    - MP 187 (PWR)
    - TN-68 (BWR)
    - MP 197 (PWR)
    - TS 125 (PWR)
  - Truck
    - NAC-LWT (PWR & BWR)
    - GA (PWR)
- 5 Specialty casks (all rail)
  - NAC-STC for Yankee Rowe
  - NAC-STC for Yankee Class
  - NAC-UMS for Maine Yankee
  - HI-STAR for Trojan
  - TS125 for Big Rock Point
- 17 cask types for the model
- Rail cask costs from $ 4-7 million
- Truck cask costs from $2.5-3 million

Example What-If's

		Budget		
Scenario	Scenario Description	2008	2009	2010
1	7 Day Turnaround; 3 Days Site Loading	No Limit		
2	14 Day Turnaround; 3 Days Site Loading	No Limit		
3	14 Day Turnaround; 6 Days Site Loading	No Limit		
4	14 Day Turnaround; 6 Days Site Loading	$25M	$25M	$35M
5	14 Day Turnaround; 6 Days Site Loading	$15M	$15M	$25M

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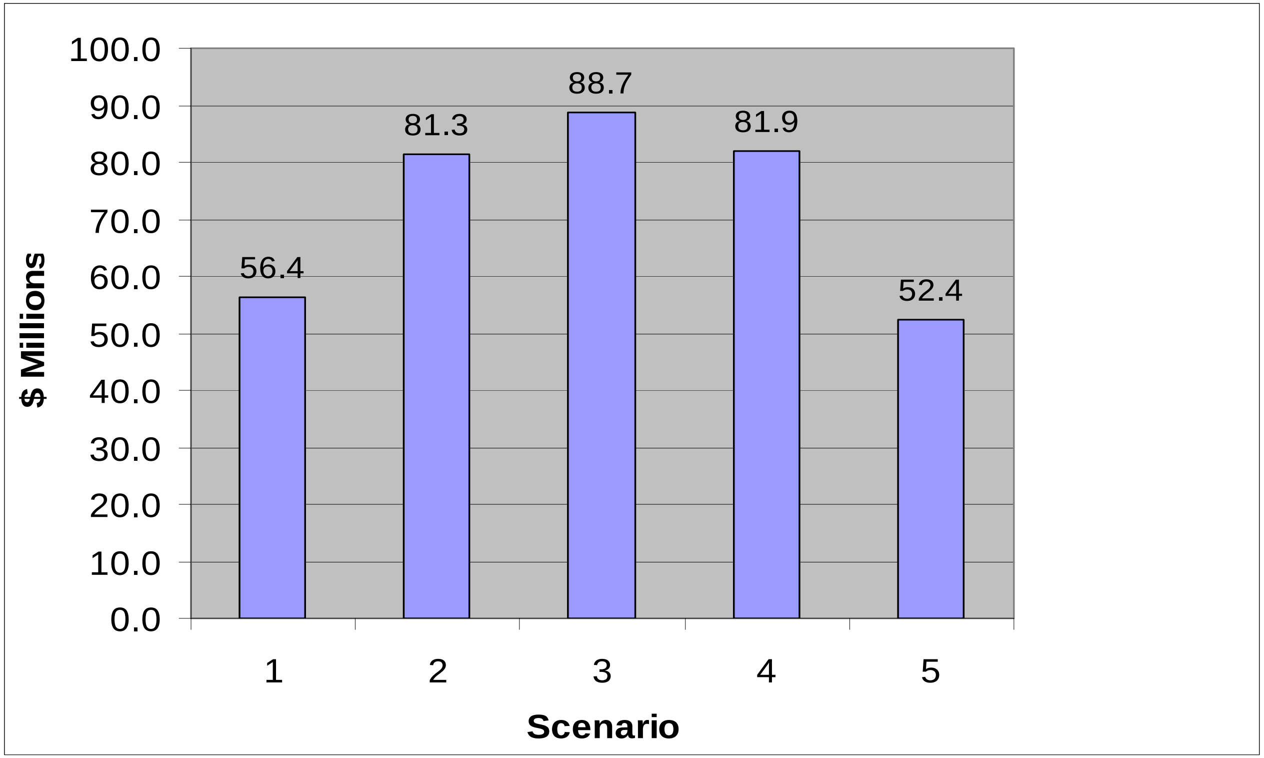
Analysis of Scenarios

Acquisition Costs



Analysis of Scenarios

Total Casks Acquired

Scenario	Total Rail Casks	Total Truck Casks	Total Casks
1	5	11	16
2	8	16	24
3	8	18	26
4	9	15	24
5	9	5	14

Analysis of Scenarios

Cask Costs Per MTHM

Scenario	Cask Cost/MTHM Rail ($ thousands)	Cask Cost/MTHM Truck ($ thousands)
1	11.88	85.42
2	16.61	124.68
3	17.77	136.81
4	18.59	113.53
5	18.60	87.17

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Analysis of Scenarios 1 - 5

	Requirements Violations			
Scenario	Year 1	Year 2	Year 3	Total Violations (MTHM)
1	8.4	0.0	18.6	27.0
2	5.9	0.0	21.1	27.0
3	0.0	0.6	26.4	27.0
4	8.4	0.0	28.6	37.0
5	50.2	48.6	123.9	222.7

Formulation: Assemblies Available to Ship Based on Discharge by Time Period

- ***$Q_c(t)$*** **– number of assemblies from batch *c* which are available for movement in time *t***

$$\sum_{\tau=1}^{t} Q_c(\tau) = B_c(t)$$

- **Cumulative number of assemblies from batch c which are available to move through the end of time period *t***

- ***$x_c(t)$*** **is the number of assemblies from batch *c* moved in time period *t***

$$\sum_{\tau=1}^{t} x_c(\tau) \le B_c(t) \qquad \forall c,t$$

Formulation: Calculating Cask Needs Based on Assemblies Shipped

- $Z_{cp}(t)$ **is the number of casks of type *p* moving assemblies from batch *c* in period *t***

- α^{t}_{cp} **is the number of assemblies from batch *c* that can fit in cask *p* when shipped in time period *t***

$$x_c(t) = \sum_{p \in P(c)} \alpha^{t}_{cp} Z_{cp}(t) \quad \forall c, t$$

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Formulation: Prevent Overuse of Casks

- The utilization of casks must be constrained in each period
- μ_c as the average cycle time (days) for batch *c*
- θ as the number of days in a period
- γ_p as an average utilization proportion for cask type *p*
- $W_p(t)$ as the fleet size for cask *p* in time period *t*

$$\sum_c \mu_c Z_{cp}(t) \le \kappa \gamma_p W_p(t) \qquad \forall t, p$$

Formulation: Cask Fleet Size by Period

- $a_p(t)$ **be the number of new casks of type *p* which are ordered in time period *t*, with a delivery lead time of n_p periods**

- λ_p **is the expected lifetime of casks of type *p***

$$W_p(t) = W_p(t-1) + a_p(t-n_p) - a_p(t-n_p-\lambda_p) \qquad \forall\ t,\ p$$

Formulation: Railcar and Trailer Fleet Size by Period

- ***$V_r(t)$*** **and** ***$V_h(t)$*** **be the number of rail cars and trailers available for use in period** ***t***
- ***P_r*** **and** ***P_h*** **are the set of rail and highway casks**

$$V^r(t) \geq \sum_{p \in P^r} W_p(t)$$

$$V^h(t) \geq \sum_{p \in P^h} W_p(t)$$

Formulation: Constrain the Use of Railcars and Trailers by Period

- $r(t)$ **- be the number of new railcars which are ordered in time period *t***
- $h(t)$ **- the number of new trailers which are ordered in time period *t***
- m^r **- delivery lead time for rail cars**
- m^h **- delivery lead time for trailers**

$$V^r(t) = V^r(t-1) + r(t - m^r) \quad \forall t$$

$$V^t(t) = V^t(t-1) + h(t - m^h) \quad \forall t$$

Formulation: Can't Order Casks Before Certification and Don't Order More Then Can be Fabricated

- K_p be the time period t that cask p becomes available
- y be the year index
- $S_p(y)$ is the maximum number of casks of type p which can be purchased in year y
- φ is the number of periods in a year

$$a_p(t) = 0 \qquad \forall p, t < K_p$$

$$\sum_{t'=y\varphi+1}^{(y+1)\varphi} a_p(t') \le S_p(y) \qquad \forall y$$

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Formulation: Requirements

- DOE must move specific amounts of materials across specific sets of batches by certain points in time
- In 2010 they must move 400 metric tons
- In 2011 they must move 1000 metric tons, etc.
- Specify a set of requirements J
- For each requirement *j* there is an initial date *I(j),* a due date, *T(j),* and a set of batches which can be used to fulfill that requirement, $R_c(j)$
- Each assembly in each batch counts δ_c towards meeting that requirement

$$\sum_{t=I(j)}^{T(j)} \sum_{c \in R_c(j)} \delta_c x_c(t) \geq R(j) \qquad \forall j$$

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Formulation: Respect the Acceptance Limits at the Repository

- ***M(t)*** **be the maximum number of casks that can be accepted at Yucca Mountain in time period *t***

$$\sum_{c}\sum_{p} Z_{cp}(t) \leq M(t) \qquad \forall t$$

Formulation: Objective of Minimize Costs

Discount Rate

$$Min\sum_{t}\rho(t)\zeta^{r}r(t)+\sum_{t}\rho(t)\zeta^{h}h(t)+\sum_{t,p}\rho(t)\beta_{p}a_{p}(t)$$

Cost for a railcar

Cost for a trailer

Cost for a cask of type *p*

Key Inputs

Each model experiment can include:

- **How much of each material (age, dimensions, heat) will be available for movement from each location over time**
- **Asset acquisition terms**
  - **Purchase cost or least cost and length of lease**
  - **Earliest purchase/lease date**
  - **Delivery lead time**
  - **Length of life**
- **Transportation routes (modes and distances) for each campaign**
- **MTHW targets for the first 6 months and each successive year**
- **Utility transportation allocation (assemblies per year)**
- **Prohibitions against picking up a certain sites during certain time periods**
- **Turnaround time at Yucca Mountain for casks, railcars and trailers**
- **Length of time for loading at the sites**
- **Acceptance rate at Yucca over time**
- **Maximal average thermal load of casks shipped**

Key Questions in Developing the Database Requirements

- What “entities” to we need to keep track of?
- What “relationships” do they have to one another?
- What specific pieces of data do we need about each entity?
- What “outputs” are needed to support better decisions?
- How should we summarize what we know to support those decisions?

Entities

- Reactors
- Sites
- Batches of assemblies
- Routes
- Casks
- Repository
- Trucks
- Railcars
- etc.

Relationships (Examples)

- May be several reactors at a site
- Batches from a given reactor may be stored at another site
- Each site may have several routes to Yucca Mountain, but only one will be selected at a time
- Batches must "fit" into casks (size, heat output, shielding requirements, etc.)

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Describing Entities (Batch Example)

• Batch ID	1922
• Reactor	Brunswick 1
• Current Site	Harris
• Year of Discharge	1979
• Number of assemblies	17
• Metric Tons	3.1686
• Cladding	Zircaloy
• Enrichment	2.11%
• Burnup	12.46 GwD/MTHM

Describing Entities (Reactor Example)

• Reactor ID	12
• Reactor Name	Brunswick 1
• Site	Brunswick
• Reactor Type	BWR
• Reactor Design	GE-4
• Fuel Length	177.8 inches
• Utility Owner	Progress Energy

Describing Entities (Site Example)

• Site ID	6
• Site Name	Brunswick
• State	North Carolina
• Latitude	33.97 N
• Longitude	78.02 W
• Selected Route	34

Outputs Needed (Examples)

- Cask Acquisition
  - For example, contract for 8 TN-68 casks in 2008, to be delivered in 2010
- Truck and Railcar Acquisition
- Movement Plan
  - For example, batch 1922 will be moved to Yucca Mt. in the third quarter of 2011, using rail and a TN-68 cask
- Shipment Summaries
  - For example, 47 metric tons of heavy metal will be moved out of Virginia in 2012
  - 12.7 metric tons of heavy metal will be moved out of Progress Energy sites in 2010
  - 28 casks will move by rail through the state of Missouri in 2011

Simulation Modeling of Border Crossings : The Peace Bridge (U.S.)

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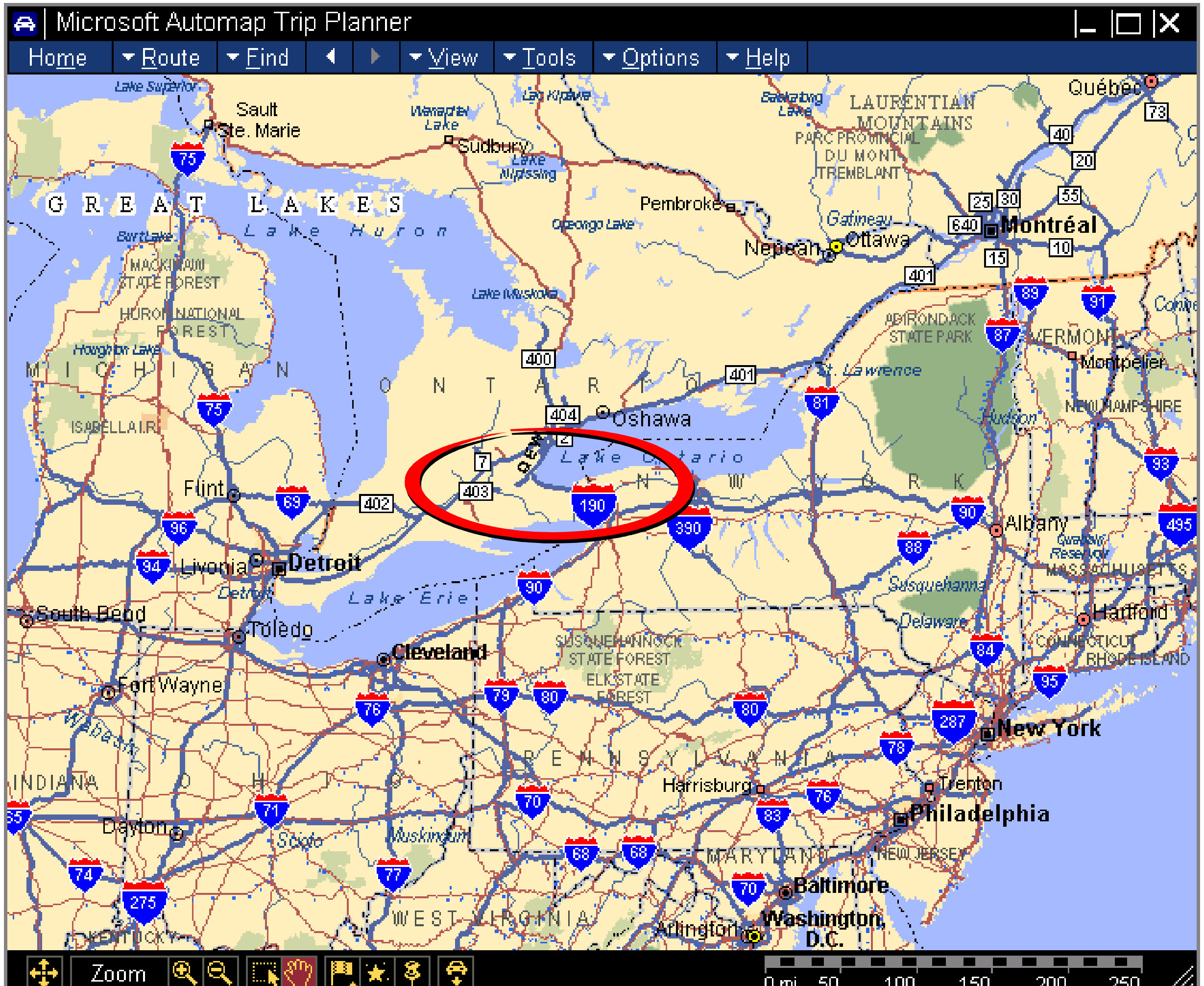
Outline

- Review the problem
- Data collection/Distribution fitting
- Fit data for time in primary for cars
- Kinds of questions we can ask
- Output analysis in general

Objective

- Motivation: NAFTA committed the US, Mexico and Canada to facilitating the flow of money, people and goods between the three member nations
- Trade between the US and Canada has grown by about 135% in the last 10 years. Now it exceeds $400B annually.
- Objective: Investigate the Effect of Employing Advanced Technology on Service Quality and Resource Use
- Client: U.S. Federal Highway and the Peace Bridge Authority

Peace Bridge



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Queue at Primary

Primary Inspection

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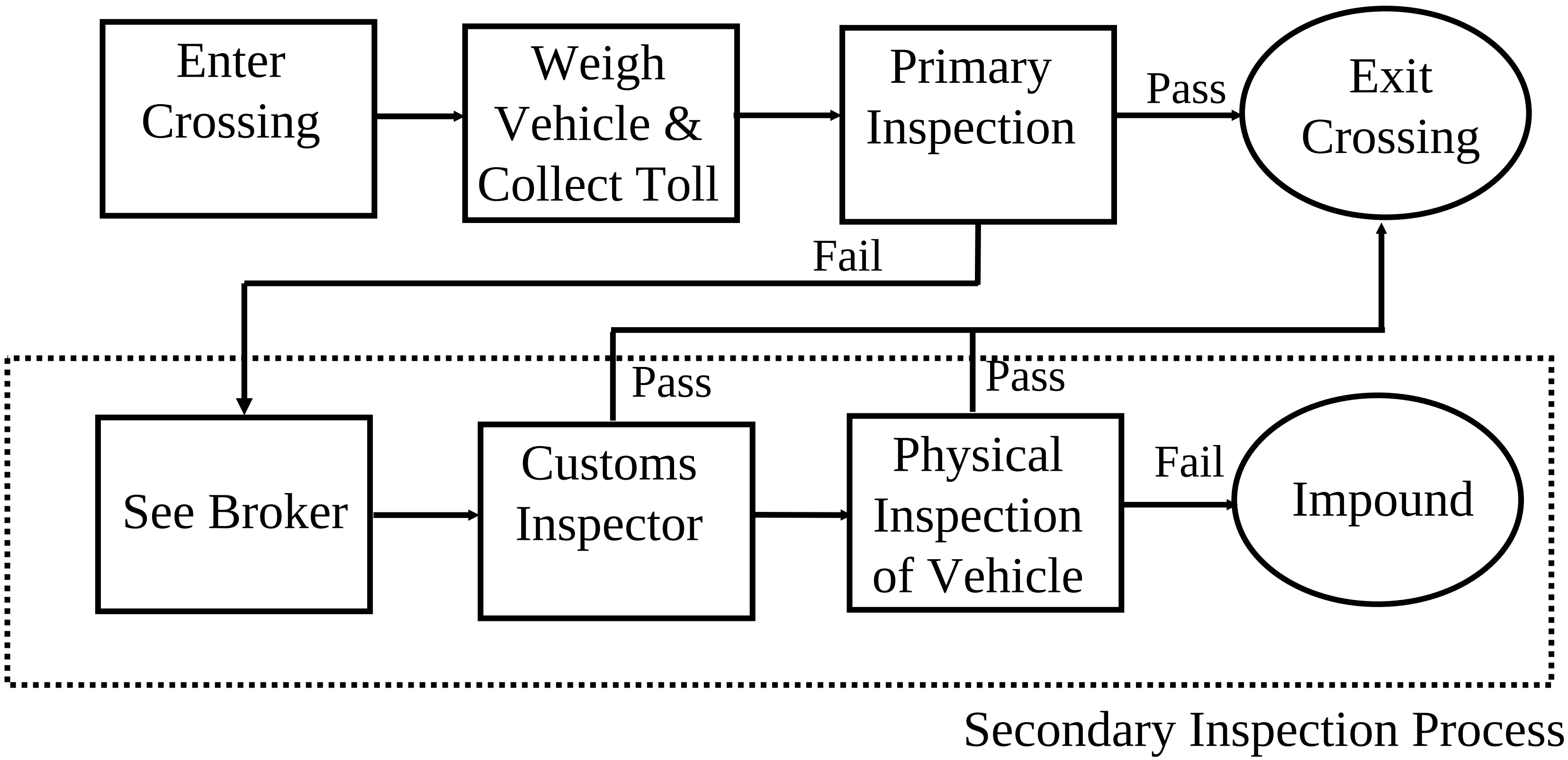
Secondary Inspection

U.S. Entry Process



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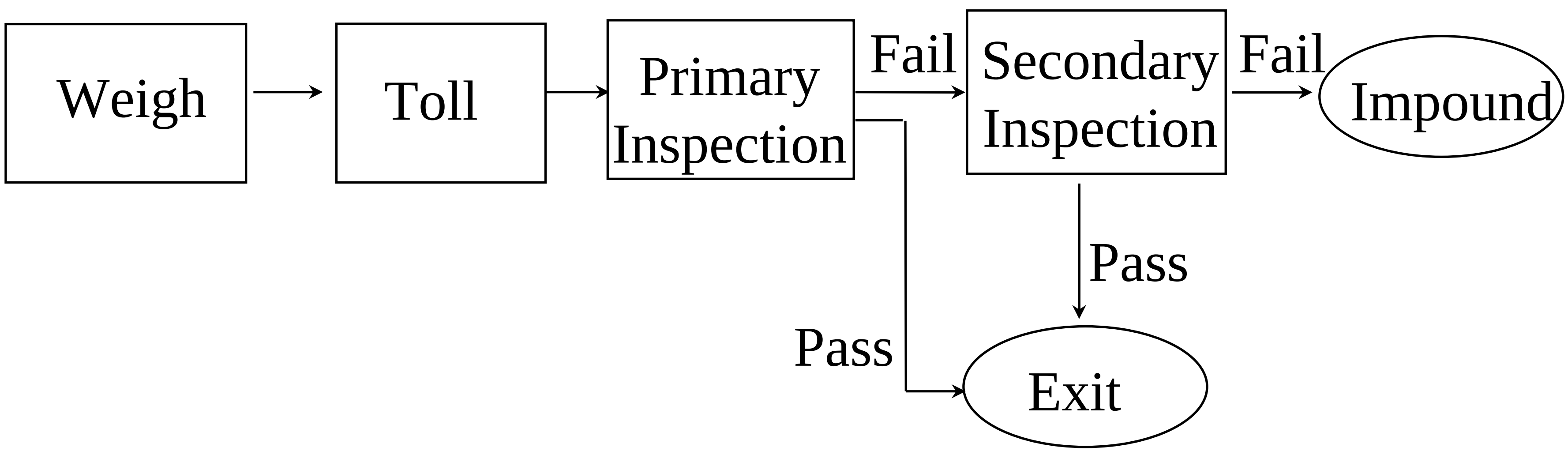
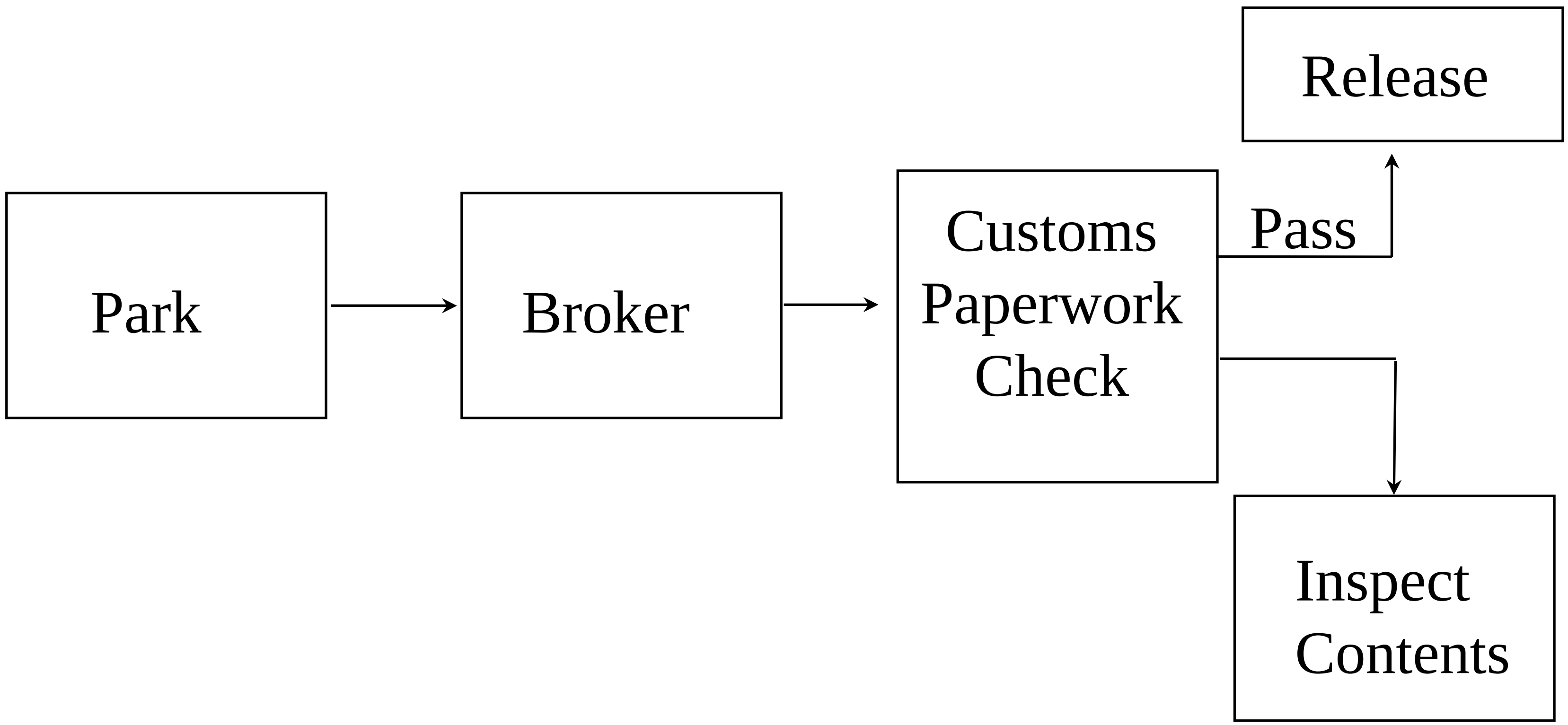
Crossing Process at the Border

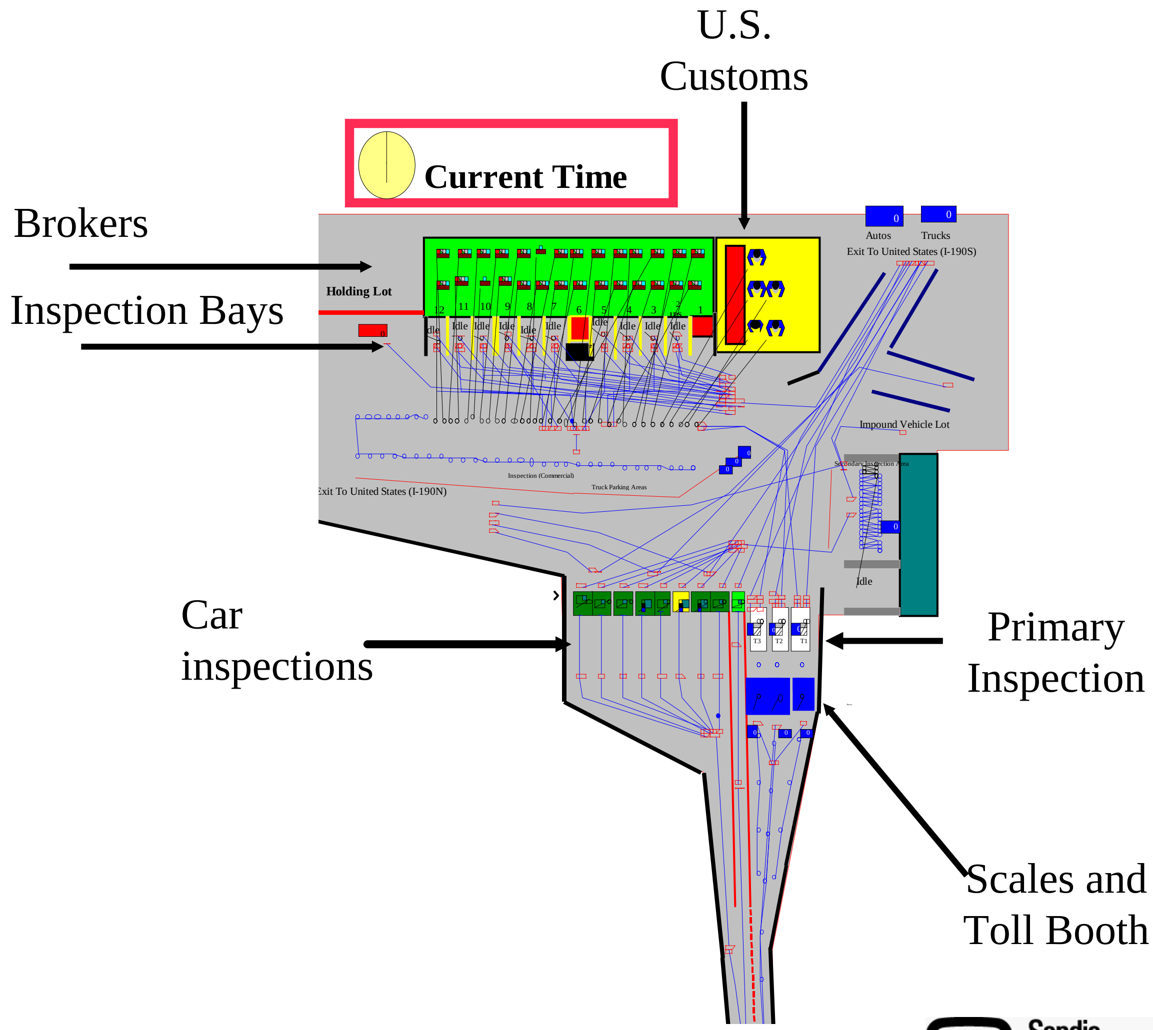


Secondary Inspection Process



Modeling Approach

- Generic Border Crossing Steps
- Simulation Model (ARENA)
- Input Data ("Peace Bridge")
- ITS-Driven Traffic Shift Impact Analysis



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Arrival Rates and Traffic Classes

- Arrival Rates are Higher in the Afternoon
- Traffic Classes (e.g. - Base Case)
  - Empty (13%)
  - Monthly/InTransit (5%)
    - Monthly
      - almost "precleared"
      - paperwork filed on a monthly basis
      - almost never go to secondary
      - most are carrying autoparts
    - InTransit
      - Destination is outside the US
  - Line Release (48%)
    - expedited crossing program
  - General (34%)

Data Collection and Distribution Fitting

- Cameras to record arrivals to the system at different locations
- Cameras to observe service times
- Examples
  – Truck interarrival times to the US Plaza from Canada (eastbound on the bridge)
  – Distribution of time in primary at the US plaza (aggregate distribution across all categories)

Estimating Distributions: Example Interarrival times to US Plaza from Canada, Feb 6th, 12 noon-1 PM

52	109	32	5	37	15	13	29	50
5	28	34	67	4	5	42	107	30
20	5	57	38	4	3	53	56	18
4	7	30	7	12	4	26	6	6
56	44	3	15	8	78	9	50	16
13	5	15	25	23	75	11	31	17
5	5	35	11	60	13	34	65	34
34	14	22	65	5	13	4	16	
12	12	17	51	4	12	4	8	
84	5	69	18	8	6	45	56	
53	2	19	48	28	25	13	36	
17	61	5	11	9	41	6	14	
29	16	5	1	4	5	42	49	
72	37	6	5	24	36	9	51	
73	24	59	21	22	31	48	115	

127 observations
Average is 1 arrival every 28 seconds
Variance between arrivals is 605 seconds

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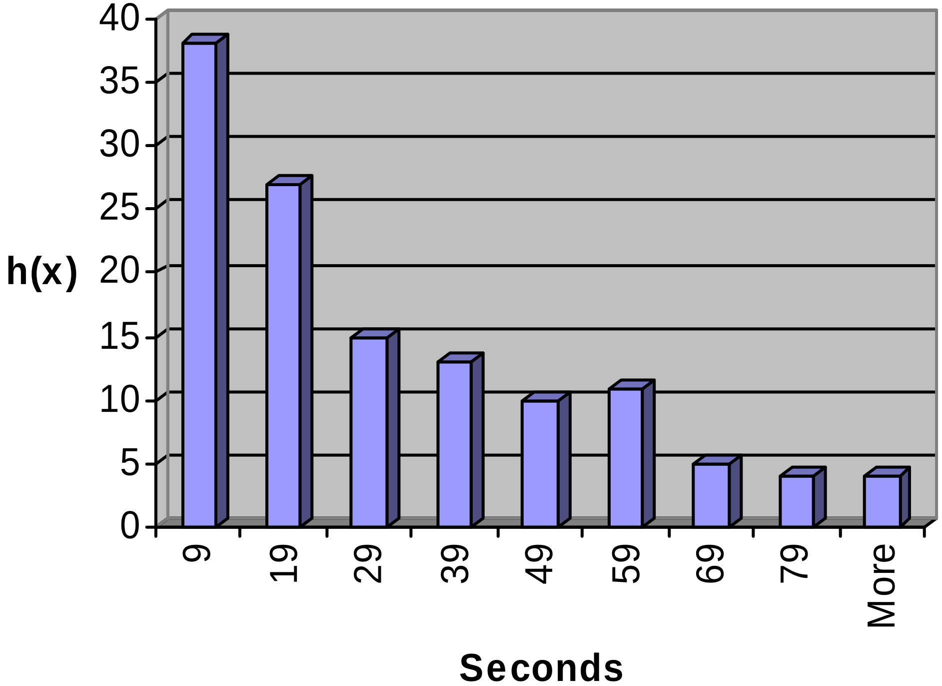
Create a Histogram

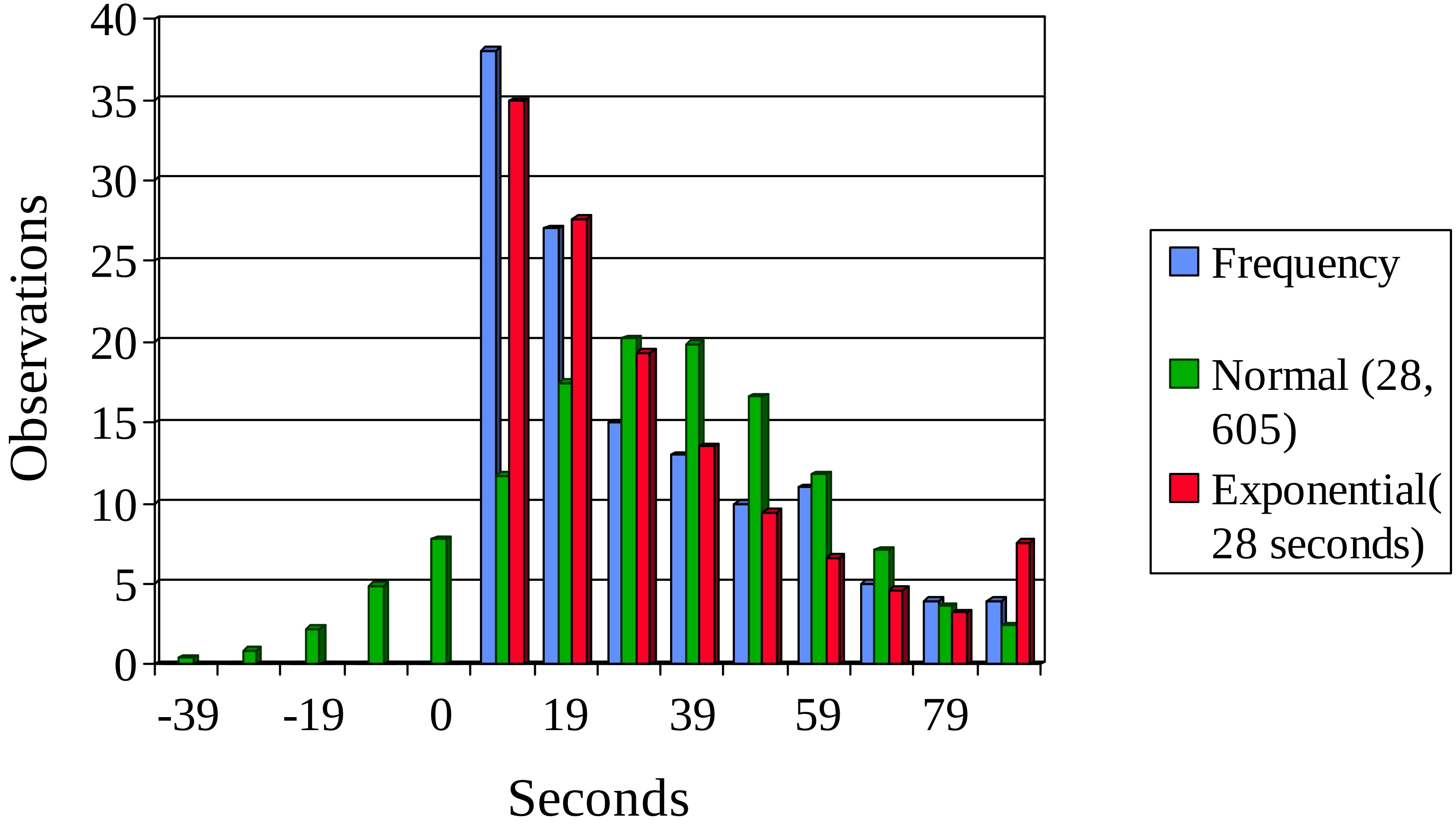


What distribution does this remind you of ?

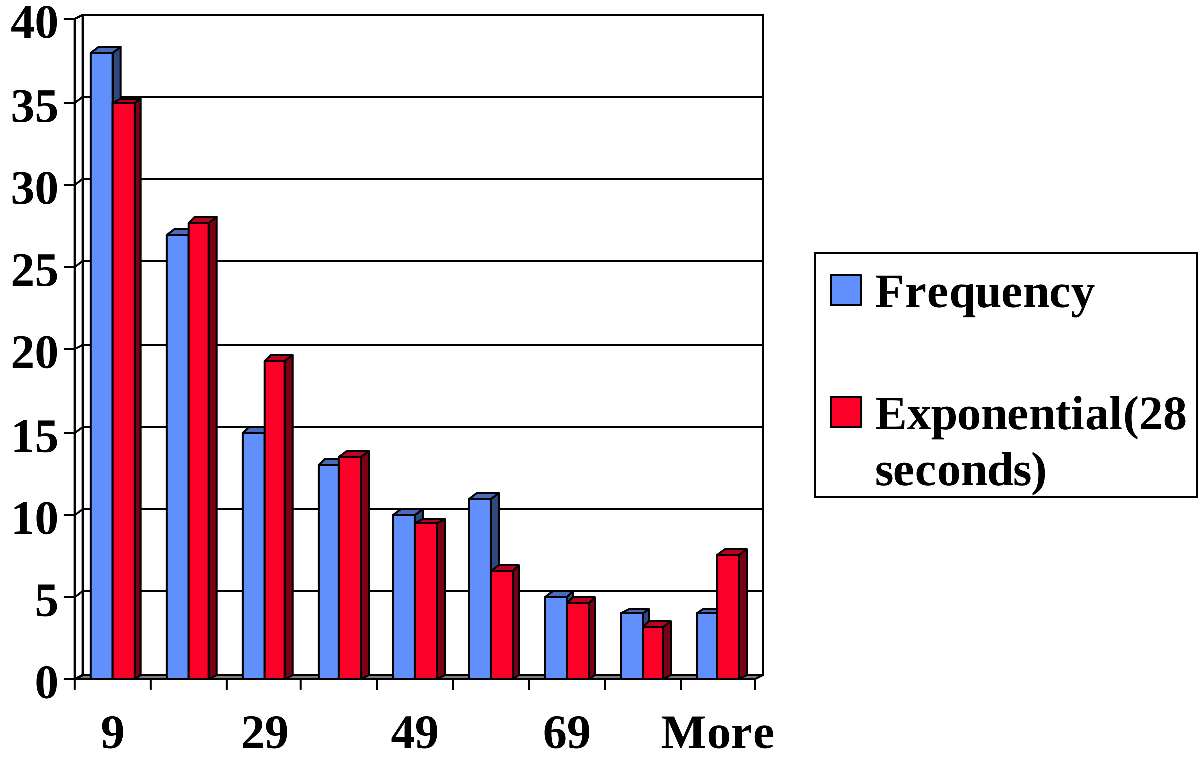
Average is 1 arrival every 28 seconds

Variance 605 seconds

Comparison of Data with what would be expected



How good is the fit?



Goodness of Fit Hypothesis test

- How well a statistical model fits a set of observations.
- Summarizes the discrepancy between observed and expected values
- Chi-Square statistic (Binomial Case)
- Test Statistic

$$\chi^2 = \sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j}$$

Where the range of data is broken up into k adjacent ranges

n is the number of observations in the data set

p_j is the proportion of observations which should fall in the j^{th} range if the theoretical distribution is correct (accepted rule: $np_j>=5$)

- Rule

$$\chi^2 > \chi^2_{k-1,1-\alpha}$$

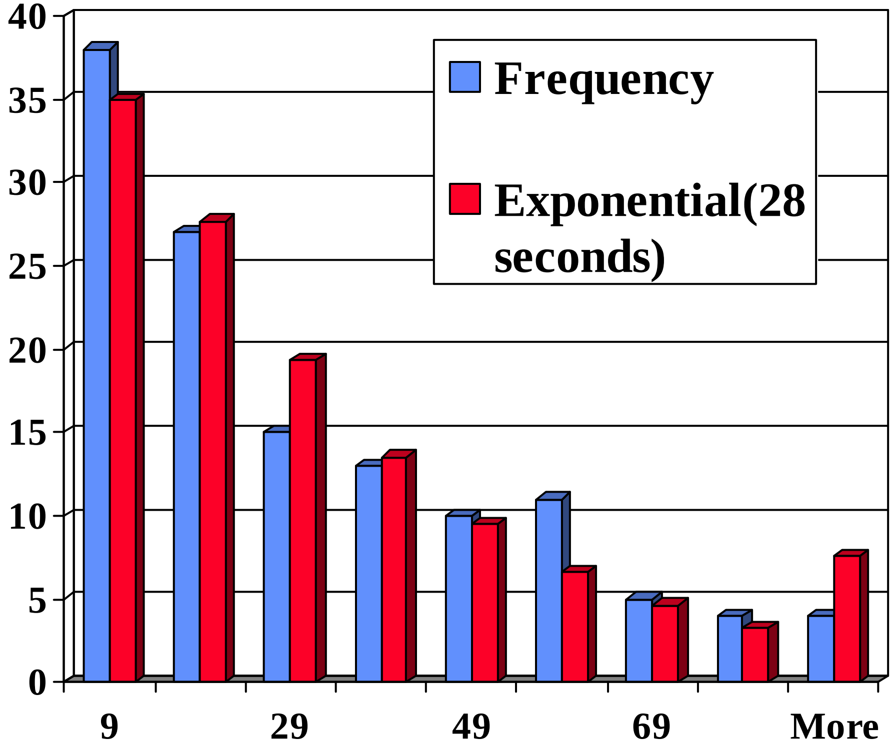
Table of Values

Table T.2 Critical points $\chi^2_{\nu,\gamma}$ for the chi-square distribution with ν df

($\gamma = P\{Y_\nu \le \chi^2_{\nu,\gamma}\}$, where Y_ν has a chi-square distribution with ν df; for large ν, use the approximation for $\chi^2_{\nu,\gamma}$ in Sec. 6.4.1)

	γ						
ν	0.250	0.500	0.750	0.900	0.950	0.975	0.990
1	0.102	0.455	1.323	2.706	3.841	5.024	6.635
2	0.575	1.386	2.773	4.605	5.991	7.378	9.210
3	1.213	2.366	4.108	6.251	7.815	9.348	11.345
4	1.923	3.357	5.385	7.779	9.488	11.143	13.277
5	2.675	4.351	6.626	9.236	11.070	12.833	15.086
6	3.455	5.348	7.841	10.645	12.592	14.449	16.812
7	4.255	6.346	9.037	12.017	14.067	16.013	18.475
8	5.071	7.344	10.219	13.362	15.507	17.535	20.090
9	5.899	8.343	11.389	14.684	16.919	19.023	21.666
10	6.737	9.342	12.549	15.987	18.307	20.483	23.209
11	7.584	10.341	13.701	17.275	19.675	21.920	24.725
12	8.438	11.340	14.845	18.549	21.026	23.337	26.217
13	9.299	12.340	15.984	19.812	22.362	24.736	27.688
14	10.165	13.339	17.117	21.064	23.685	26.119	29.141
15	11.037	14.339	18.245	22.307	24.996	27.488	30.578
16	11.912	15.338	19.369	23.542	26.296	28.845	32.000
17	12.792	16.338	20.489	24.769	27.587	30.191	33.409
18	13.675	17.338	21.605	25.989	28.869	31.526	34.805
19	14.562	18.338	22.718	27.204	30.144	32.852	36.191
20	15.452	19.337	23.828	28.412	31.410	34.170	37.566
21	16.344	20.337	24.935	29.615	32.671	35.479	38.932
22	17.240	21.337	26.039	30.813	33.924	36.781	40.289
23	18.137	22.337	27.141	32.007	35.172	38.076	41.638
24	19.037	23.337	28.241	33.196	36.415	39.364	42.980
25	19.939	24.337	29.339	34.382	37.652	40.646	44.314
26	20.843	25.336	30.435	35.563	38.885	41.923	45.642
27	21.749	26.336	31.528	36.741	40.113	43.195	46.963
28	22.657	27.336	32.620	37.916	41.337	44.461	48.278
29	23.567	28.336	33.711	39.087	42.557	45.722	49.588
30	24.478	29.336	34.800	40.256	43.773	46.979	50.892
40	33.660	39.335	45.616	51.805	55.758	59.342	63.691
50	42.942	49.335	56.334	63.167	67.505	71.420	76.154
75	66.417	74.334	82.858	91.061	96.217	100.839	106.393
100	90.133	99.334	109.141	118.498	124.342	129.561	135.807

How good is our hypothesized Exponential?



Intervals	Data	Exp(28 sec)	Tabulation of statistic
9	38	34.91	0.27
19	27	27.66	0.02
29	15	19.35	0.98
39	13	13.54	0.02
49	10	9.47	0.03
59	11	6.63	2.88
69	5	4.64	0.03
79	4	3.24	0.18
More	4	7.56	1.68
			6.08

9 intervals

At alpha=0.05, then critical=15.5
p-value is close to 0.75

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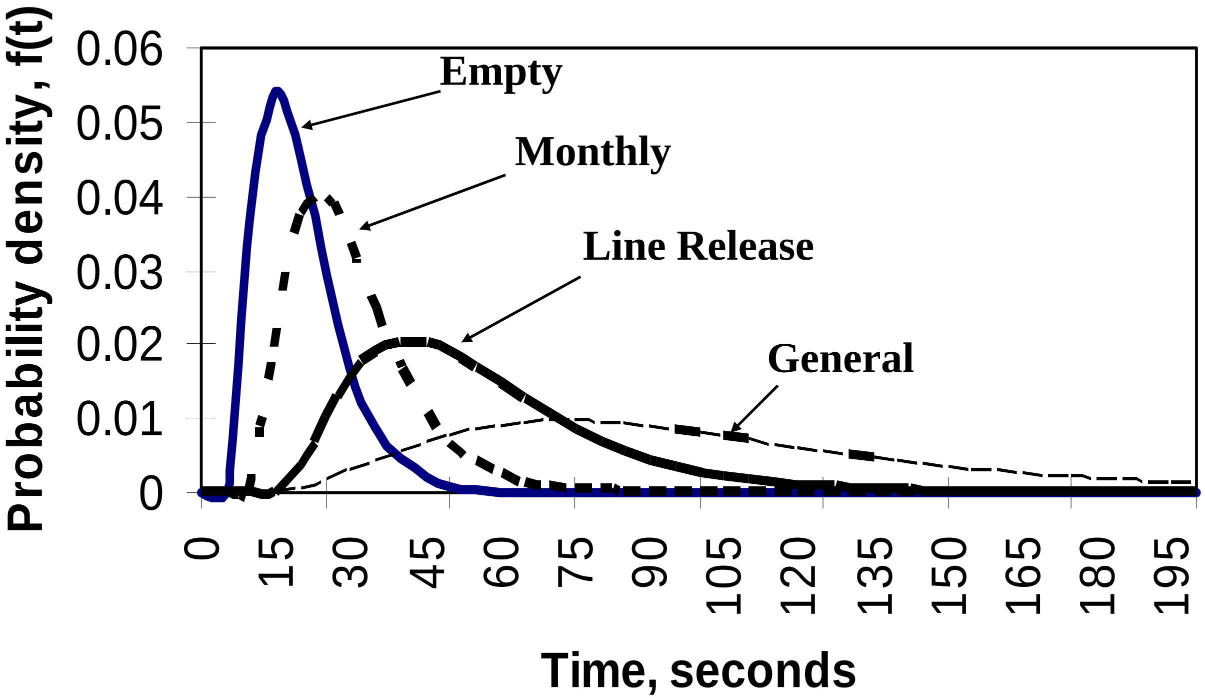
McCormick-Rankin Study

	McCormick-Rankin Study	Videotape
# Observations	6,887	129
Mean	57 seconds	37 seconds
Variance	Not reported	1,632 seconds
% below 1 minute	57%	86%
% below 3 minutes	97%	98%
% below 5 minutes	99%	99%

Distributions for Time in Primary



Failure Rate at Primary

Traffic Class	Percent of Traffic	Primary Failure Rate
Empty	13%	~0%
Monthly	5%	~0%
Line Release	48%	~5%
General	34%	~90%

Probability of a Cargo Inspection in Secondary ~10%

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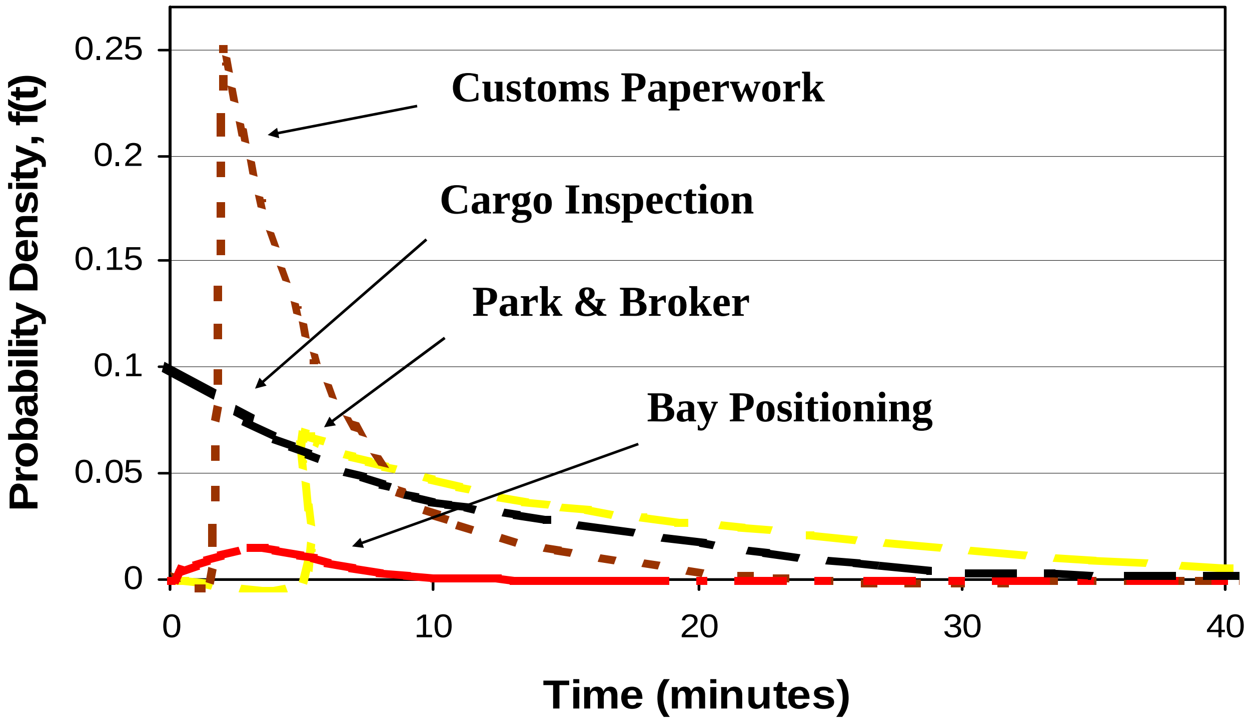
Secondary Processing Times



System Performance Measures

- Utilization of primary and secondary inspectors and toll collectors
- Average time in system by traffic category
- Time in primary queue
- Diurnal pattern in the number of vehicles parked in the secondary area

Postulated Penetration Rates for Advanced Technology

Truck Category	Base Case	"10%L" Scenario	"20%L" Scenario	"10%G" Scenario	"20%G" Scenario	"Low" Scenario	"Med" Scenario	"High" Scenario
AdvTech	0%	10%	20%	10%	20%	10%	30%	60%
Empty	13%	13%	13%	13%	13%	12%	10%	6%
Monthly/ In-Transit	5%	5%	5%	5%	5%	1%	1%	0%
Line Release	48%	38%	28%	48%	48%	43%	29%	10%
General	34%	34%	34%	24%	14%	34%	30%	24%

- **Advanced Technology**
  - **Primary inspection times are assumed equivalent to empty (mean in primary of 20s)**
  - **Zero probability of being referred to the secondary area**
  - **No dedicated lanes**
  - **Conservative assumptions**

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Average Time in System for the Base Case

Truck Category	Average Time in System (minutes)	95% Confidence Interval (minutes)
Empty	7.7	7.0 – 8.4
Monthly/In-Transit	7.9	7.3 - 8.5
Line Release	10.9	10.3 - 11.5
General	57	51 - 63

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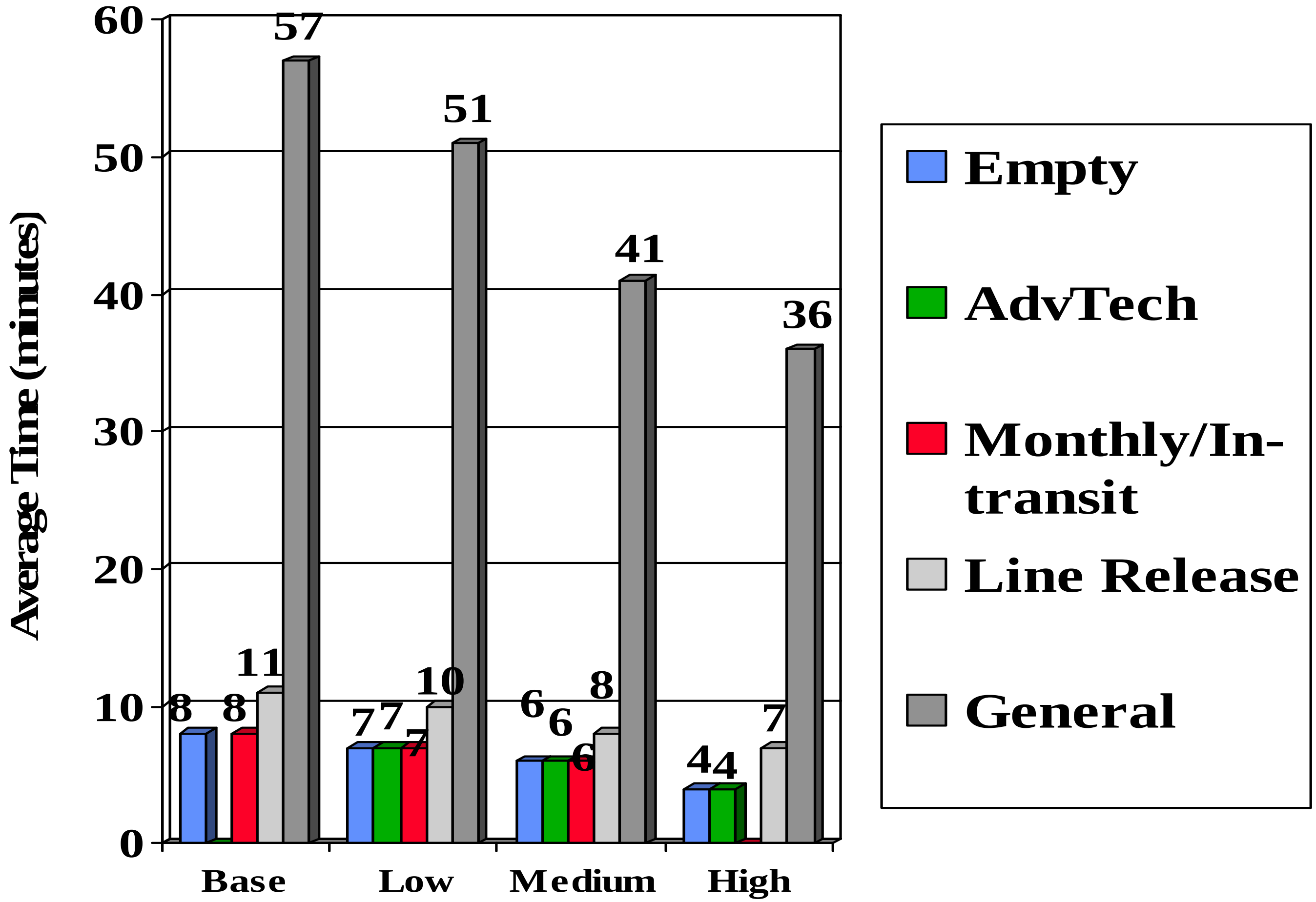
Average Time In System for Select Shifts



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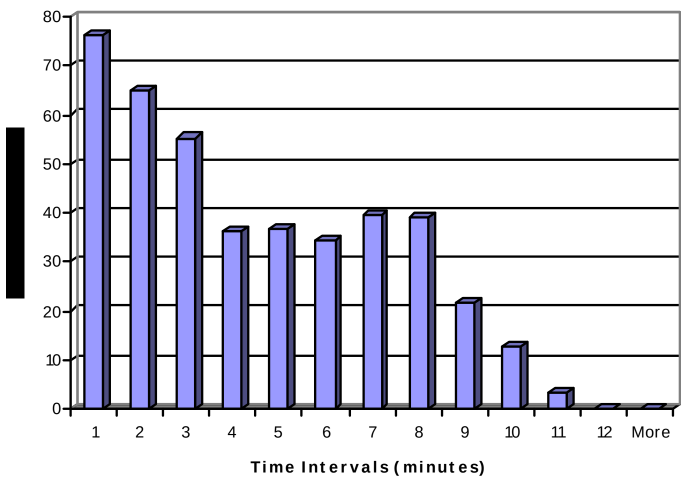
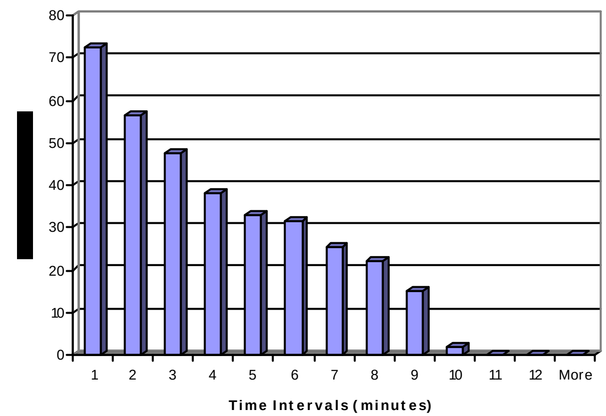
Histogram of Time in Queue for Select Shifts

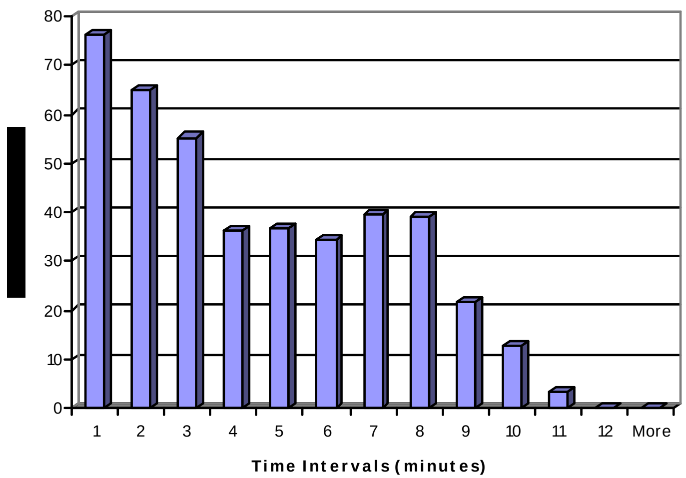


Base Case

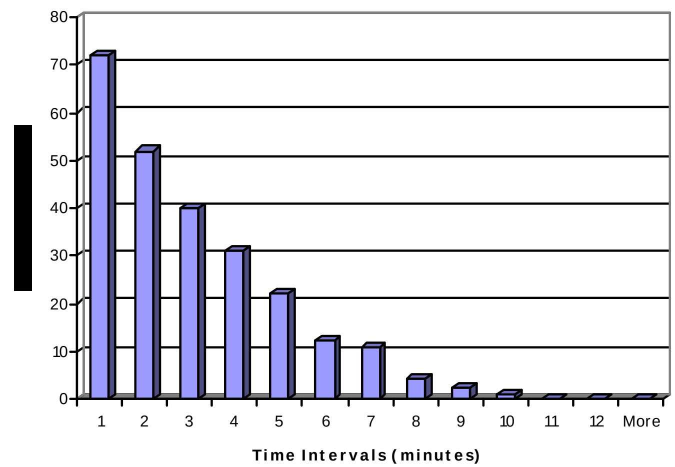


10% Shift from Line Release

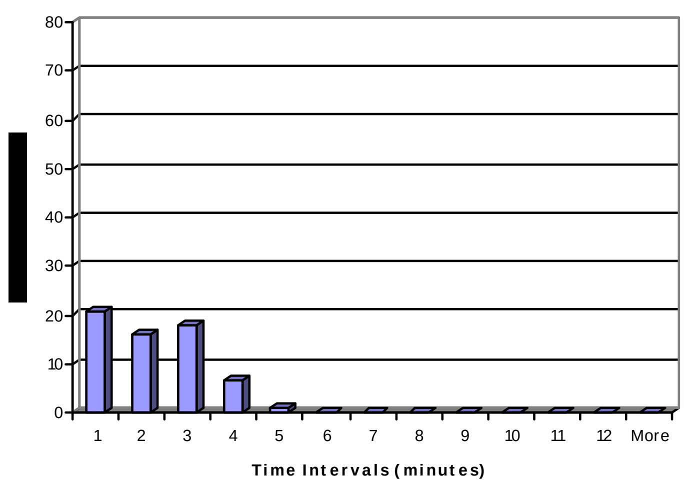
Histogram of Time in Queue for Select Shifts



Base Case

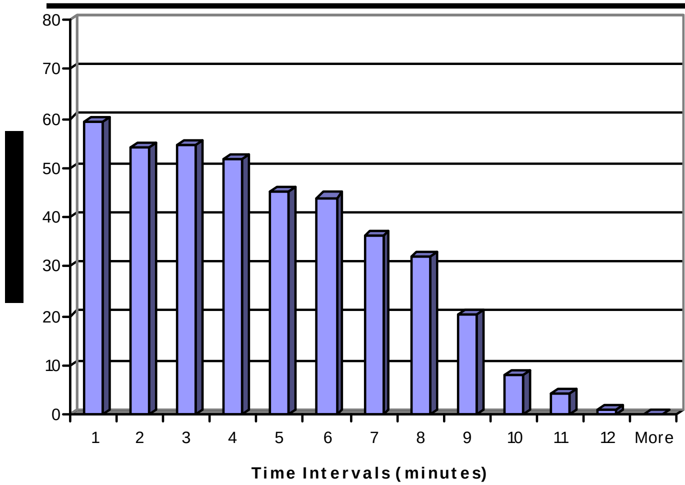


10% Shift from General

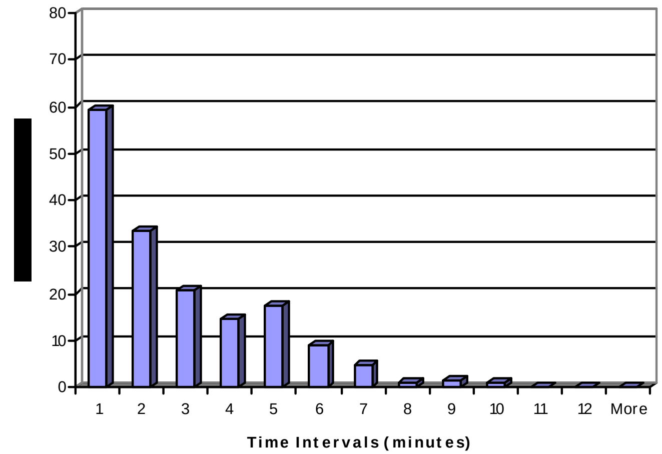


20% Shift from General

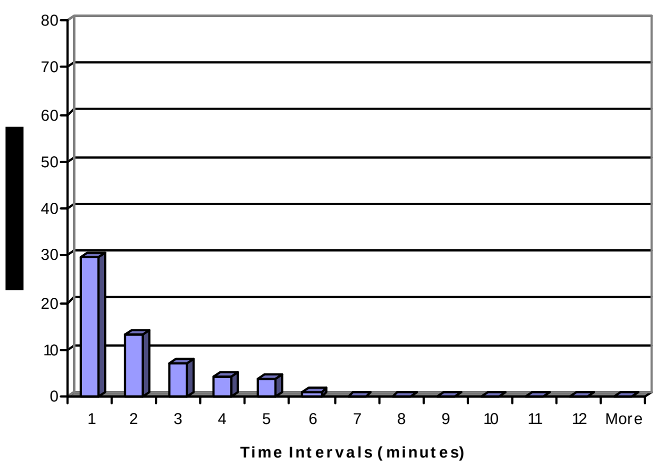
Histogram of Time in Queue for Select Shifts



Low Penetration Rate



Medium Penetration Rate



High Penetration Rate

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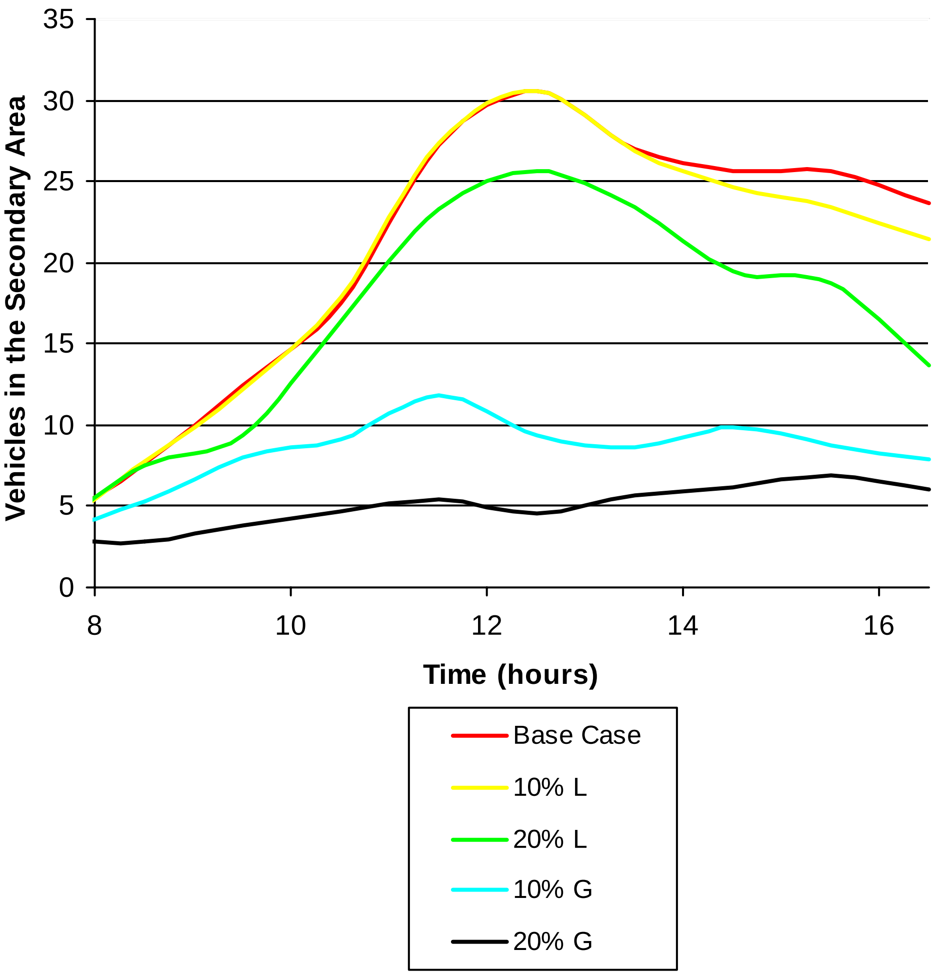
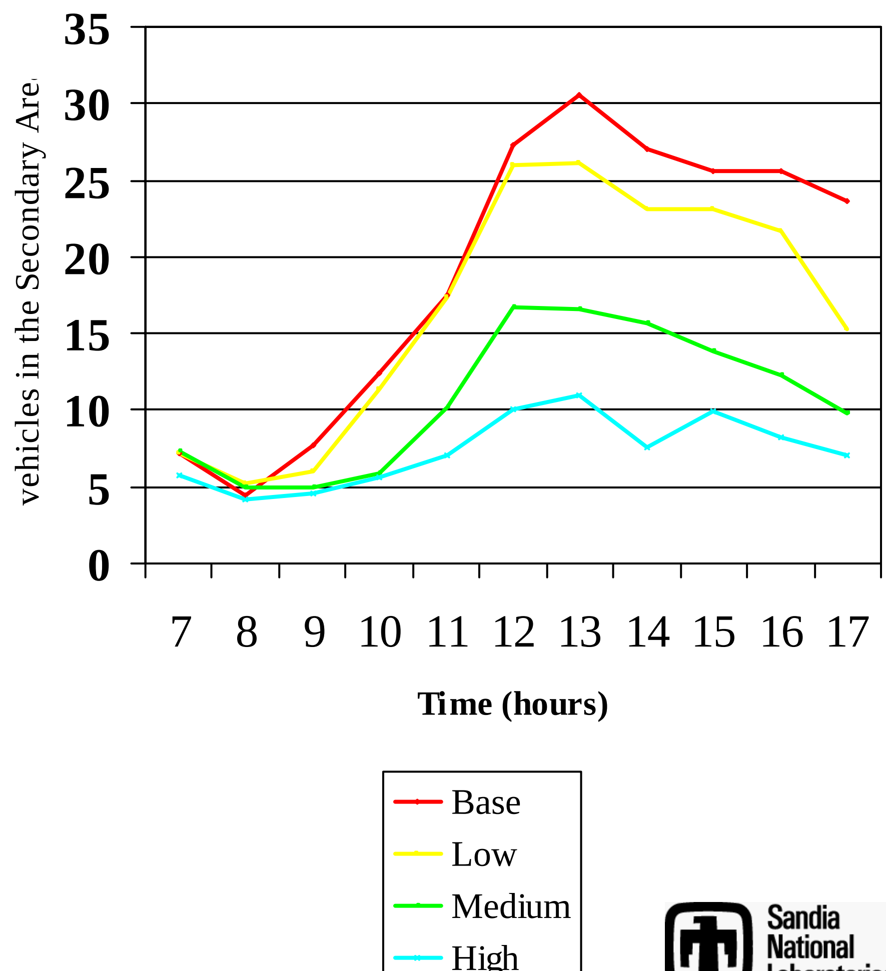
Vehicles in the Secondary Area





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Resource Use