U. S. Department
of Transportation
**Federal Highway
Administration**

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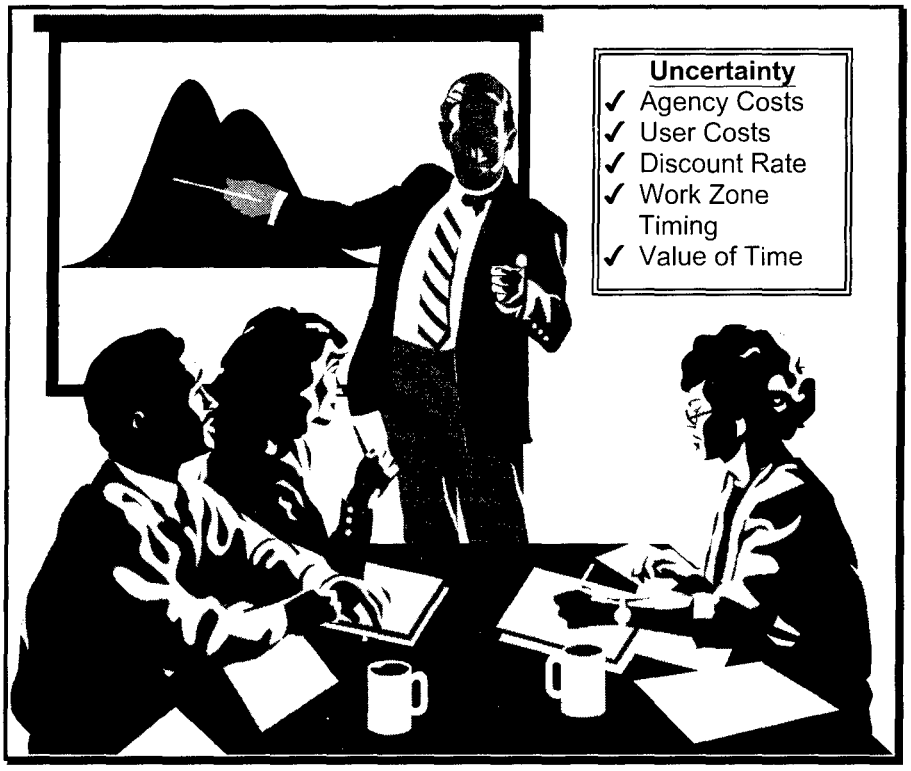
**August 1998**

PB99-107419

# Life-Cycle Cost Analysis in Pavement Design Participant's Notebook




## Demonstration Project No. 115

## Foreword

This participant's notebook was developed by FHWA staff to compliment a 2-day workshop on life cycle cost analysis in pavement design. This workshop will be of interest to State highway agency personnel responsible for conducting and/or reviewing pavement design LCCAs.

The FHWA Office of Engineering, Pavement Division, in cooperation with the Office of Technology Applications, offers LCCA technical support through Demonstration Project No. 115 *Probabilistic LCCA in Pavement Design* (DP-115). DP-115 is a free 2-day workshop that demonstrates best practices in performing life-cycle cost analyses for pavement design. This workshop is available, upon request, to State highway agencies.

Henry H. Rentz, Director
Office of Engineering

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# Life-Cycle Cost Analysis in Pavement Design
# Participant's Notebook

Demonstration Project No. 115

# TABLE OF CONTENTS


Course Evaluation
Agenda
COURSE MODULES
- Module I: Overview
- Module II: Background
- Module III: LCCA Process Overview
- Module IV: Components and Issues
- Module V: Introduction to Project Level User Costs
- Module VI: Work Zone User Costs: Calculation Steps
- Module VII: Basic Statistics
- Module VIII: Risk Analysis Approach
- Module IX: Software Demonstration
- Module X: Class Exercise Revisited
- Module XI: Presentation Techniques
- Module XII: Benefits and Implementation
- Module XIII: Summary

Class Exercises
Class Exercises - Solutions

# Participant Evaluation Form

**Course Title:** Life Cycle Cost Analysis in Pav't Design **Dates:** _____

**Instructor(s):** _____ **Location:** _____

Please help us improve the training by evaluating the training course and workshop in which you participated. Your input is appreciated and needed. You may use the back of this form for additional comments.

| ***Please rate this workshop in the following areas:*** | **Excellent** | **Very Good** | **Good** | **Fair** | **Poor** |
|---|---|---|---|---|---|
| ▪ Adequate coverage of subject matter | 5 | 4 | 3 | 2 | 1 |
| ▪ Applicable to your current job | 5 | 4 | 3 | 2 | 1 |
| ▪ Meeting room location | 5 | 4 | 3 | 2 | 1 |
| ▪ Course materials | 5 | 4 | 3 | 2 | 1 |
| ▪ Knowledge gained from this workshop | 5 | 4 | 3 | 2 | 1 |
| ▪ This workshop overall | 5 | 4 | 3 | 2 | 1 |
| ***Please rate the instructor(s) in the following areas:*** | | | | | |
| ▪ Organization | 5 | 4 | 3 | 2 | 1 |
| ▪ Presentation | 5 | 4 | 3 | 2 | 1 |
| ▪ Clarity of instruction | 5 | 4 | 3 | 2 | 1 |
| ▪ Encouraging participation | 5 | 4 | 3 | 2 | 1 |

Would you recommend this training to other department employees? _____ **Yes** _____ **No**

- Comments: (Please note exceptional points and/or clarify fair or poor ratings below)

_____

_____

_____

_____

_____

_____

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_____

## Two Day Agenda

| | Time | Title |
|---|---|---|
| Day 1 | 08:00 am | *Welcome* |
| | 08:15 am | Workshop Overview |
| | 08:30 am | Background |
| | 09:00 am | LCCA Process Overview |
| | 09:30 am | *Break* |
| | 09:45 am | Components & Issues |
| | 10:45 am | *Break* |
| | 11:00 am | Class Exercise No. 1 or 2 |
| | 12:00 am | *Lunch* |
| | 01:00 pm | Introduction to Work Zone User Costs |
| | 01:30 pm | Work Zone User Costs: Calculation Steps |
| | 02:45 pm | *Break* |
| | 03:00 pm | Class Exercise No. 3 |
| | 04:00 pm | Class Exercise No. 4 |
| | 05:00 pm | *Close for Day* |
| Day 2 | 08:00 am | Basic Statistics |
| | 09:00 am | Risk Analysis Approach |
| | 10:00 am | *Break* |
| | 10:15 am | Software Demonstration |
| | 12:00 pm | *Lunch* |
| | 01:00 pm | Class Exercise Revisited |
| | 02:00 pm | Presentation Techniques |
| | 02:30 pm | *Break* |
| | 02:45 pm | Benefits & Implementation |
| | 03:30 pm | Workshop Summary |
| | 04:00 pm | Question & Answers – Workshop Evaluations |
| | 05:00 pm | *Closeout* |

## Three Day Agenda

| | Time | Title |
|---|---|---|
| Day 1 | 01:00 pm | *Welcome* |
| | 01:15 pm | Workshop Overview |
| | 01:30 pm | Background |
| | 02:00 pm | LCCA Process Overview |
| | 02:30 pm | *Break* |
| | 02:45 pm | Components & Issues |
| | 03:45 pm | *Break* |
| | 04:00 pm | Class Exercise No. 1 or 2 |
| | 05:00 pm | *Close for Day* |
| Day 2 | 08:00 am | Introduction to Work Zone User Costs |
| | 08:30 am | Work Zone User Costs: Calculation Steps |
| | 09:45 am | *Break* |
| | 10:00 am | Class Exercise – No. 3 |
| | 11:00 am | Class Exercise – No. 4 |
| | 12:00 pm | *Lunch* |
| | 01:00 pm | Class Exercise - No. 4 Continued |
| | 02:00 pm | Basic Statistics |
| | 03:00 pm | *Break* |
| | 03:15 pm | Risk Analysis Approach |
| | 04:15 pm | Software Demonstration |
| | *05:00 pm* | *Close for the Day* |
| Day 3 | 08:00 am | Class Exercise Revisited |
| | 09:00 am | Presentation Techniques |
| | 09:30 am | *Break* |
| | 09:45 am | Benefits & Implementation |
| | 10:30 am | Workshop Summary |
| | 11:00 am | Question & Answers – Workshop Evaluations |
| | 12:00 pm | *Closeout* |

1

# Workshop Overview

2

## Project Team

Max Grogg, 518-431-4224 x 223

Keith Herbold, 708-283-3548

Michael Smith, 202-366-4057

James Walls, 202-366-1339

3

- Arizona DOT Larry Scofield
- Penn DOT Gaylord Cumberledge (retired)
- Ohio DOT Roger Green
- Montana DOT Dick Clark
- ACPA James Mack
- NAPA Ken Hansen
- University Washington Joe Mahoney

4

## DP-115 Phases

1. Traditional approach and *Introduce* probabilistic concepts
2. SHA Case Studies
3. Application of Probabilistic Approach

5

## Phase I Objective

- Provide training and practice on traditional LCCA
- Introduce probabilistic concepts

6

## Workshop Outline

- Background
- Process Overview
- Components and Issues
- User Costs
- Class Exercises
- Basic Statistics
- Probabilistic Approach
- LCCA Probabilistic Example
- Benefits and Implementation

7

## Major Focus ...

- LCCA process overview
- Components and issues
- User cost procedure
- *Introduce* Probabilistic approach

8

## End Session

1


2

## Session Overview

- Definitions
- Levels of Application
- Driving Forces
- Implementing Guidance
- National Pavement Design Review

3

## Definitions

- Life Cycle Cost Analysis
- Agency Cost
- User Cost
- Deterministic Approach
- Risk Analysis Approach

4

## LCCA Defined (NHS)

"A process for evaluating the total economic worth of a useable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

5

## Useable Project Segment

A portion of a highway that when completed could be opened to traffic independent of some larger overall project.

6

## TEA 21 (98) LCCA Defined

Life-cycle cost analysis is a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoration, and resurfacing costs, over the life of the project segment.

7

## Agency Costs

- Design and Engineering
- Initial Construction
- Maintenance of Traffic
- Maintenance
- Rehabilitation

8

## User Costs

Costs incurred by users of a highway facility including excess costs to those who cannot use the facility because of agency or self-imposed detour requirements.

9

## Deterministic Approach

The application of accepted LCCA procedures and techniques without regard for the variability of input factors.

10

## Risk Analysis Approach

A technique which identifies the variability associated with LCCA input factors and carries this variability through the computation process to generate results in the form of a probability distribution.

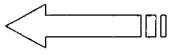
11

## Session Overview

- Definitions
- Levels of Application
- Driving Forces
- Implementing Guidance
- National Pavement Design Review

12

## Levels of Application

- Funding levels
- Program allocation
- Project selection
- Design selection 

13

## Session Overview

- Definitions
- Levels of Applications
- Driving Forces
  - ISTEA (91)
  - FHWA-AASHTO Symposium (93)
  - Executive Order 12893 (94)
  - NHS Designation Act (95)
  - TEA 21 (98)
  - NQI Survey (95)

14

## ISTEA (1991)

- Sections: 1024 & 1025

Factors to be *considered* ...

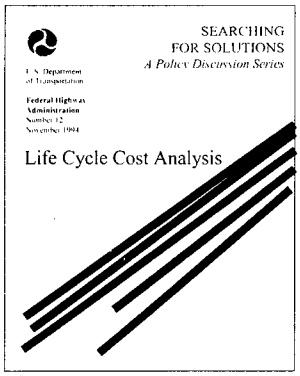
the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavements.

15

## LCCA Symposium (93)

- AASHTO Survey
- Focused attention on LCCA
- Spotlighted issues
- No Resolutions

16




Publication No. FHWA-PL-94-025

17

## Executive Order 12893 (94)

"Principles for Federal Infrastructure Investments"

- Directed at Federal Agencies
- Grant Programs
- Initiated FHWA Policy Statement

18

## NHS Designation Act (95)

Section 303, "Quality Improvement,"

... requires States to conduct LCCA of each NHS high cost ($25M or more) useable project segment.

19

## TEA 21 (98)

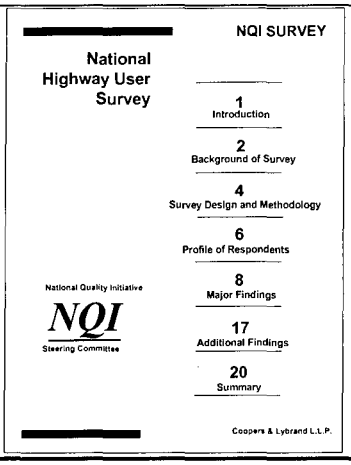
- LCCA no longer mandated
- Adds Users Costs to LCCA def.
- Directs DOT to develop LCCA procedures based on principals contained in Exec. Order 12893
- Transportation Research Program addresses analysis period, discount rates, user costs, ...

20

## National Quality Initiative

- National Policy on Quality of Highways (92)
- Survey conducted (11/95)

21



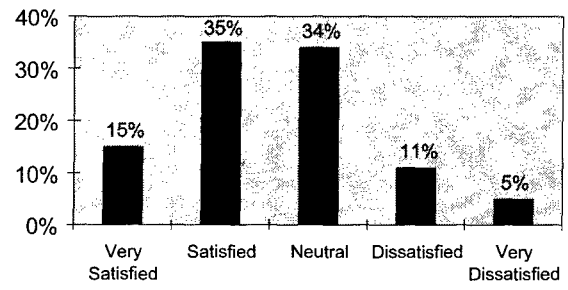
22

## Survey Highlights

- Overall satisfaction
- Pavement condition
- Maintenance response time
- Traffic flow

23

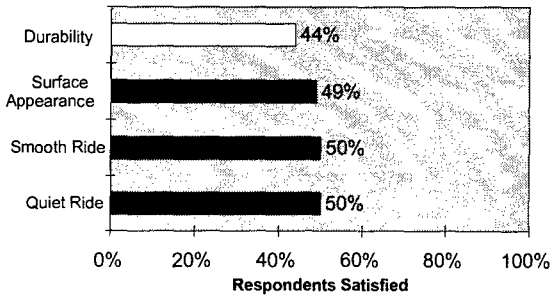
## Overall Satisfaction with Highway System




Opportunity to improve public satisfaction.

24

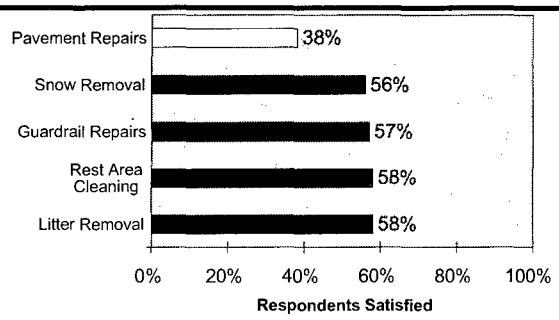
## Pavement Condition




Temporary repairs don't cut it !

25

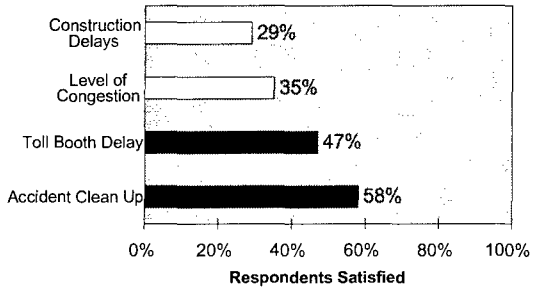
## Maintenance Response Time




Response time needs improving !

26

## Traffic Flow




Get in, fix it, and get out !

27

## NQI Survey Priorities ...

1. Pavement Condition
2. Safety
3. Traffic Flow

28

## Session Overview

- Definitions
- Levels of Applications
- Driving Forces
- Implementing Guidance
  - NHS - FHWA memo (4/96)
  - LCCA Policy Statement (9/96)
  - Technical Bulletin (97)
  - DP 115

29

## FHWA Memo (4/19/96)

- Federal-aid eligibility contingent on LCCA for $25 Million + NHS projects
- Defines useable project segment
- LCCA procedures not prescribed
- Focus on "good" practice

30

## LCCA Policy Statement (9/96)

FHWA Philosophy ...

- Decision support tool
- Results are not decisions
- Use process to improve maintenance and rehabilitation strategies
- Logical evaluation process is as important as results

31

## LCCA Policy Statement (9/96)

- LCCA important consideration in all highway investment decisions
- Level of detail commensurate with level of investment
- Long analysis periods
  - Pavements - min. 35 years
  - Bridges - min. 75 years

(More)

32

## Policy Statement Con't ...

- Agency and user costs should be included
- Future costs should be discounted to their *net present value (NPV)*

33

## Technical Bulletin

- State of the practice
  - Traditional approach
- User costs (work zone)
  - VOC
  - Delay
- Introduce risk analysis (probabilistic approach)

34

## DP 115

- Workshop
- Case studies
- Future activities

35

## Additional Resources

- NCHRP
  - Synthesis reports
  - MicroBencost software
- AASHTO
  - Red Book
  - Pavement Design Guide
  - Darwin

36

## Session Overview

- Definitions
- Levels of Application
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- National Pavement Design Review

37

National Pavement Design Review

- Background
- Purpose
- General Findings (LCCA)

38

## Background

- OIG/GAO reviews
- FHWA reviews 1995 - 1997
- 52 SHAs
- Areas addressed:
  - ✓ LCCA
  - ✓ Design procedures
  - ✓ Traffic

39

## LCCA General Findings

- Procedures
- Analysis Periods
- Performance Periods
- Discount Rates
- User Costs

40

## LCCA Procedures

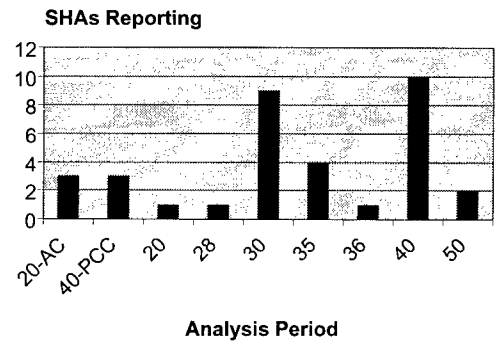
- Number Reporting ..... 52
- Documented Procedures ..... 33
  - New Location ..... 33
  - Reconstruction ..... 33
  - Major Rehabilitation ..... 22

41

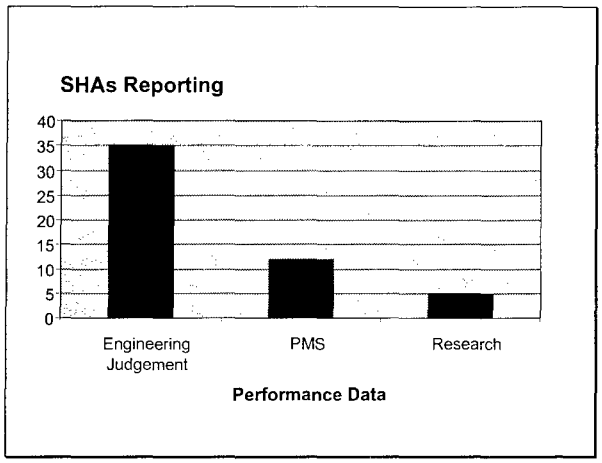
## LCCA Procedures Cont.'d

- Not Documented .....19
  - Informal Procedures .....11
  - Plan to Develop Procedure ..... 7
  - Has no Plan to Develop Procedure ..... 1

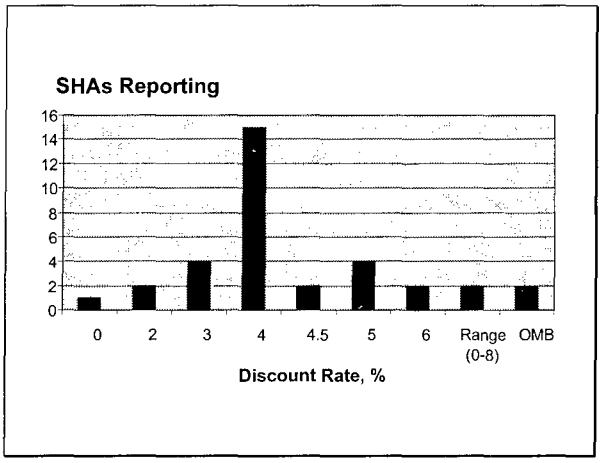
42



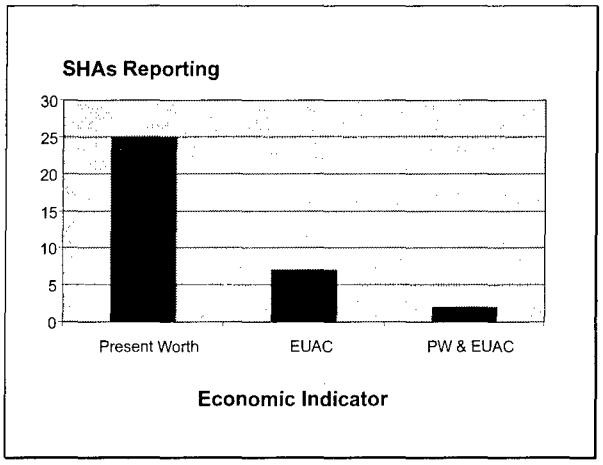
43


SHAs Reporting
40
35
30
25
20
15
10
5
0
Engineering Judgement
PMS
Research
Performance Data

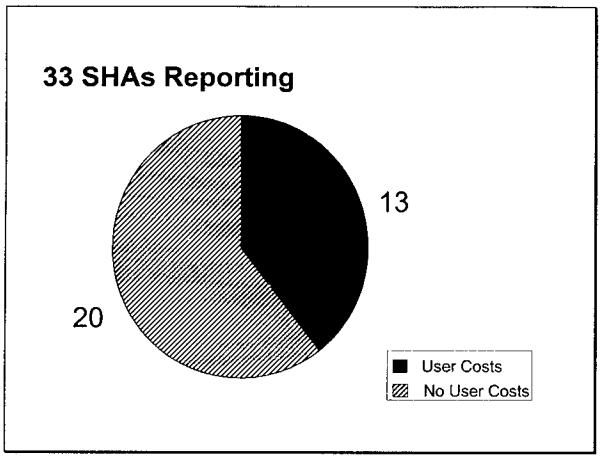
44


SHAs Reporting
16
14
12
10
8
6
4
2
0
0
2
3
4
4.5
5
6
Range (0-8)
OMB
Discount Rate, %

45


SHAs Reporting
30
25
20
15
10
5
0
Present Worth
EUAC
PW & EUAC
Economic Indicator

46




47

## Session Summary

- Definitions
- Driving Forces
- Implementing Guidance
- National Pavement Design Review

48

## End Session

1

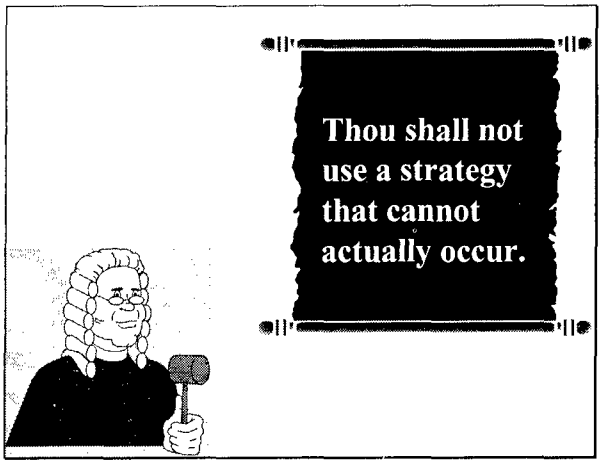
# LCCA Process Overview

2

## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure streams
6. Compute NPV
7. Analyze results
8. Reevaluate strategies

3



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## 1. Establish Strategies for Analysis Period

- Initial pavement designs
- Subsequent maintenance and rehabilitations

5

## Example: PCC M&R Activities

| Yr. | Activity |
|---|---|
| 5 | Clean & Seal Jnts, Seal Coat Shoulders |
| 10 | Same as 5 |
| 15 | Same as 5 |
| 20 | Same plus Patch & Slab Stabilization Diamond Grind & Spall Repair |
| 25 | Same as 5 |
| 30 | Patch, Overlay, Saw & Seal Joints, Pave Shoulders, Adjust Guardrail & Drainage |
| 35 | Seal Coat Shoulders |

6

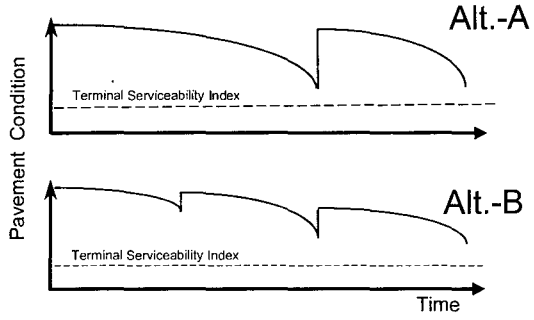
## LCCA Process Steps

❶ Establish strategies for analysis period

❷ Establish activity timing

7

## 2. Establish Activity Timing

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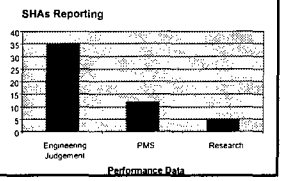
## Data Sources ...

- Local Research Studies
- Agency Personnel - Experience
- Pavement Management Systems
- National Research Studies
- Other ...

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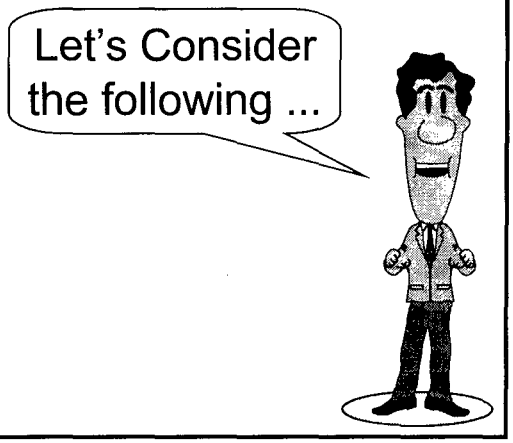


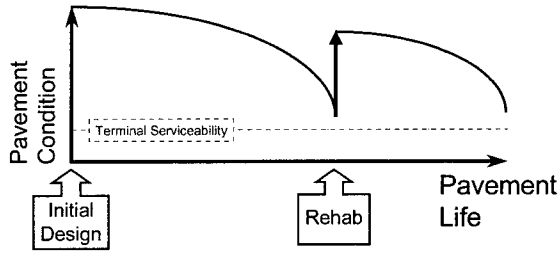
10

## Example

- Initial Construction
- Single Future Construction

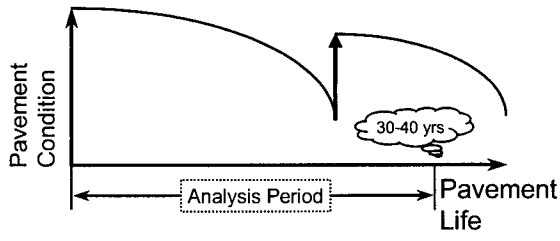
11

## Performance Curves



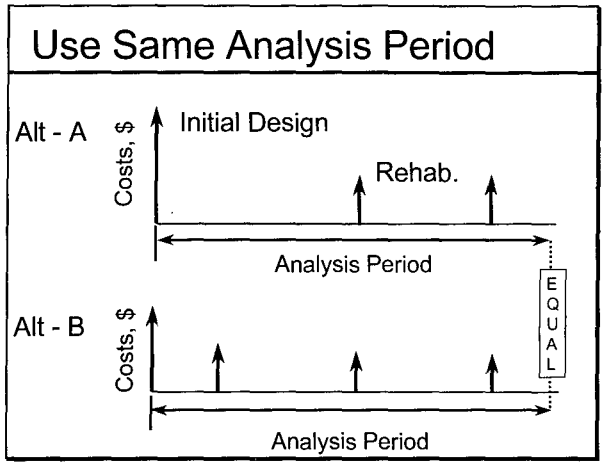

12

## Analysis Period

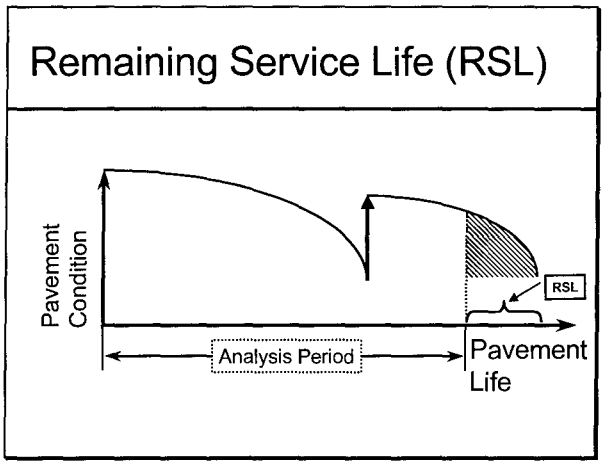



Include at least one Rehab.

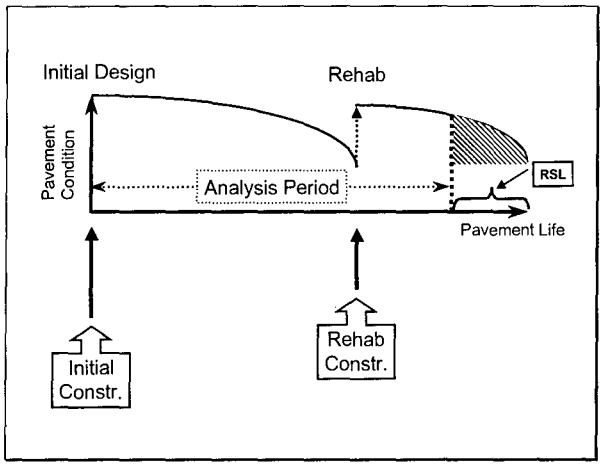
13


Use Same Analysis Period
Alt - A
Costs, $
Initial Design
Rehab.
Analysis Period
EQUAL
Alt - B
Costs, $
Analysis Period

14


Remaining Service Life (RSL)
Pavement Condition
RSL
Analysis Period
Pavement Life

15


Initial Design
Rehab
Pavement Condition
Analysis Period
RSL
Pavement Life
Initial Constr.
Rehab Constr.

16

## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs

17

## 3. Estimate Agency Costs

Agency Costs Defined ...

- Costs associated with roadway improvements
- Born by Agency

18

## Agency Cost Include ...

- Initial Construction Cost
- Future Rehab and Preventive Maint.
- Project Overhead ...
  - Preliminary Engineering,
  - Contract Administration,
  - Construction Supervision and Inspection
- Traffic Control

19

## Data Sources ...

- SHA historical bid data
- Bid Analysis Management System (BAMS)

20

## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs

21

## 4. Estimate User Costs

User Costs Defined ...

- Costs incurred by users of a highway facility including excess costs to those who do not use the facility because of agency or self-imposed detour requirements.

22

## User Costs Include ...

- Vehicle operating
- User delay
- Crash

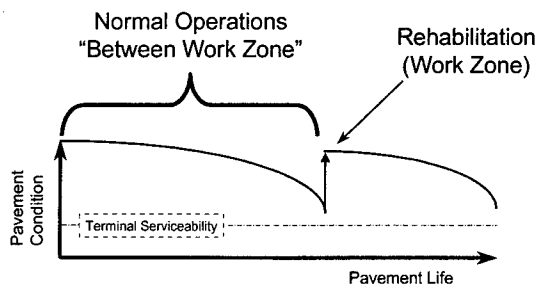
23

## User Costs

Can occur during ...

- Normal operations
- Work Zone

24



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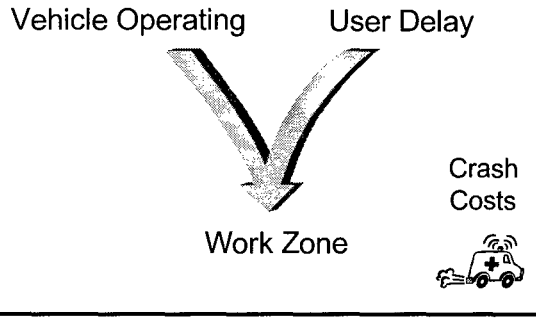
## User Costs (Normal Operations)

- Difficult to quantify
- Data suggest may be minimal if roughness is "small"

26

## Our Primary Focus ...




27

## Work Zone User Cost

Defined ...

- Excess VOC and delay costs to users of the facility during work zone operations.
- Additional VOC and delay costs to users who do not use the facility because of agency or self imposed detours.

28

## LCCA Process Steps

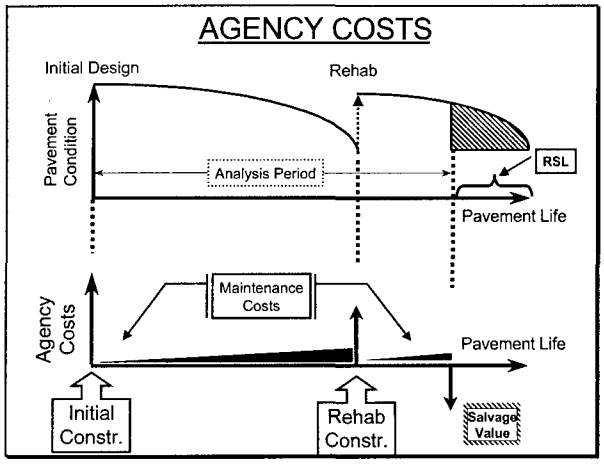
1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure streams

29

## 5. Develop Expenditure Streams

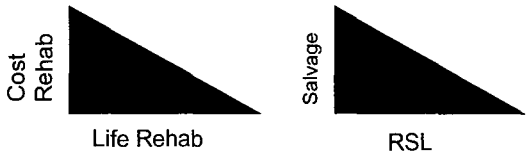
- Agency Costs
- User Costs

30



31

## Salvage Value




$$\text{Salvage Value} = \left(\frac{\text{RSL}}{\text{Life Rehab}}\right) \text{Rehab Cost}$$

32

## Routine Reactive Maintenance

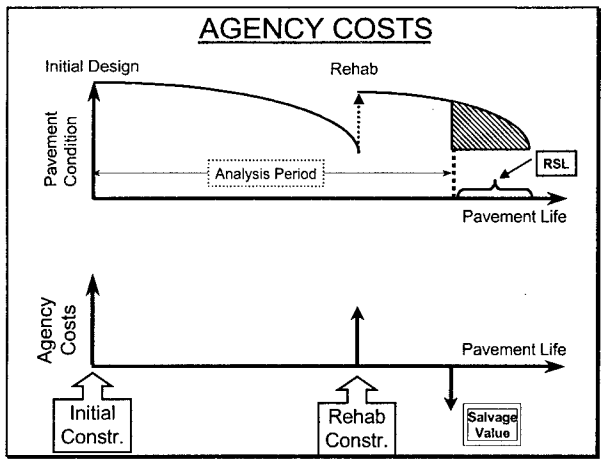
- Usually small
- When discounted its even smaller
- Can be ignored in the analysis

33

## Inflation

- Use constant dollars
- Use real discount rate

34

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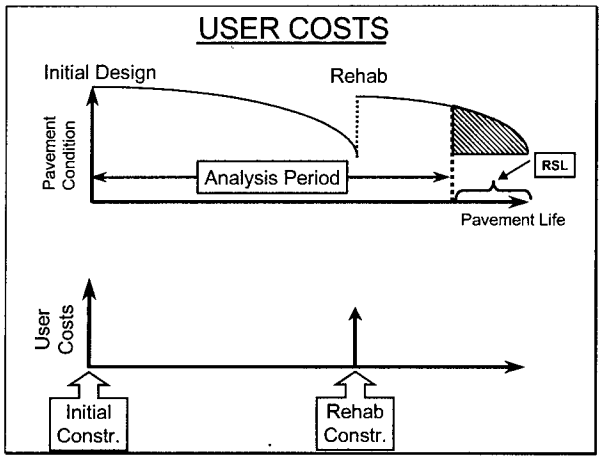



36

## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure streams
6. Compute NPV

37

## Definition

Discounted present value of benefits less discounted present value of costs.

38

## 6. NPV Equation

$$NPV = \text{Initial Cost} + \sum_{k=1}^{N} \text{Future Cost}_k \times \underbrace{\left[\frac{1}{(1+i)^{n_k}}\right]}_{\text{Present Value Factor}}$$

i = discount rate
n = year of expenditure

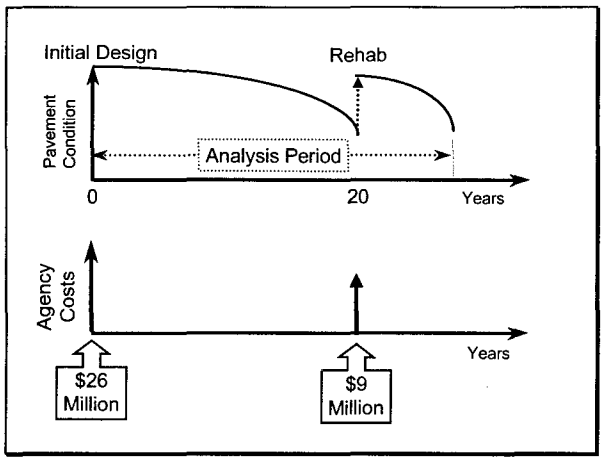
39

## Present Value Factors

| | Discount Rate (I) | | | | |
|---|---|---|---|---|---|
| Year | 4.0% | 4.5% | 5.0% | 5.5% | 6% |
| 0 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| ⋮ | ⋮ | | ⋮ | | ⋮ |

NPV = (Future Cost) x (Present Value Factor)

40




41

## Deterministic Approach

$ 30.1 M $ 26 M

NPV = Initial Cost +

Future Cost x $ 9 M

$$\left[\frac{1}{(1+i)^n}\right]$$

4% 20 yrs

42

❶ Agency NPV

❷ User NPV

Since User Costs May Dominate
Separate Agency and User Costs

43

## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure streams
6. Compute NPV
7. Analyze results

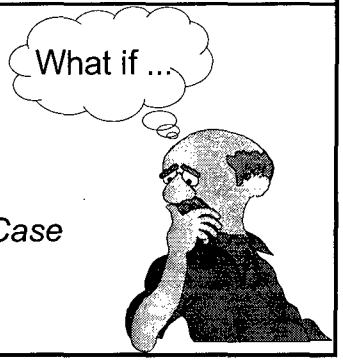
44

## 7. Analyze Results

- Weigh qualitative advantages and disadvantages of alternatives
- Determine and explain LCCA implications

45

## Sensitivity Analysis

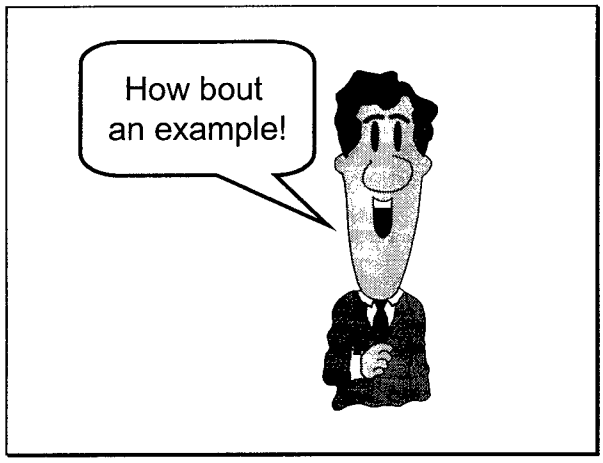



✓*Best Case*

✓*Most Likely Case*

✓*Worst Case*

**46**




**47**

Example

## Sensitivity Analysis

### Alternative - A

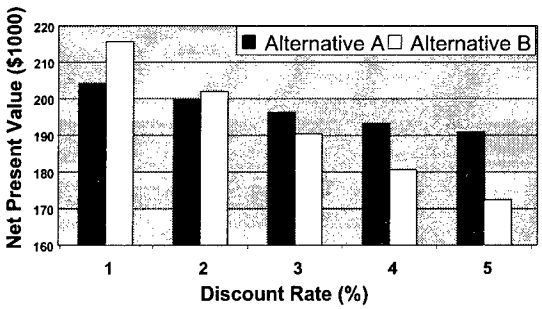
| Activity | Year | Cost | Discounted Cost 1% | 2% | 3% | 4% | 5% |
|---|---|---|---|---|---|---|---|
| Constr. | 0 | $177.0 | $177.0 | $177.0 | $177.0 | $177.0 | $177.0 |
| Rehab. | 10 | $ 10.0 | $ 9.1 | $ 8.2 | $ 7.4 | $ 6.8 | $ 6.1 |
| Rehab. | 20 | $ 15.0 | $ 12.3 | $ 10.1 | $ 8.3 | $ 6.8 | $ 5.7 |
| Rehab. | 30 | $ 15.0 | $ 11.1 | $ 8.3 | $ 6.2 | $ 4.6 | $ 3.5 |
| Salvage | 35 | $( 7.5) | $( 5.29) | $( 3.75) | $( 2.67) | $( 1.90) | $( 1.36) |
| | | NPV | $204.2 | $199.8 | $196.3 | $193.3 | $190.9 |

### Alternative - B

| Activity | Year | Cost | Discounted Cost 1% | 2% | 3% | 4% | 5% |
|---|---|---|---|---|---|---|---|
| Constr. | 0 | $125.0 | $125.0 | $125.0 | $125.0 | $125.0 | $125.0 |
| Rehab. | 15 | $ 80.0 | $ 68.9 | $ 59.4 | $ 51.3 | $ 44.4 | $ 38.5 |
| Rehab. | 30 | $ 80.0 | $ 59.4 | $ 44.2 | $ 33.0 | $ 24.7 | $ 18.5 |
| Salvage | 35 | $(53.3) | $ (37.6) | $ (26.7) | $ (18.9) | $ (13.5) | $ ( 9.7) |
| | | NPV | $215.6 | $202.0 | $190.4 | $180.6 | $172.3 |

**48**

## Sensitivity to Discount Rate



49

## Sensitivity Analysis

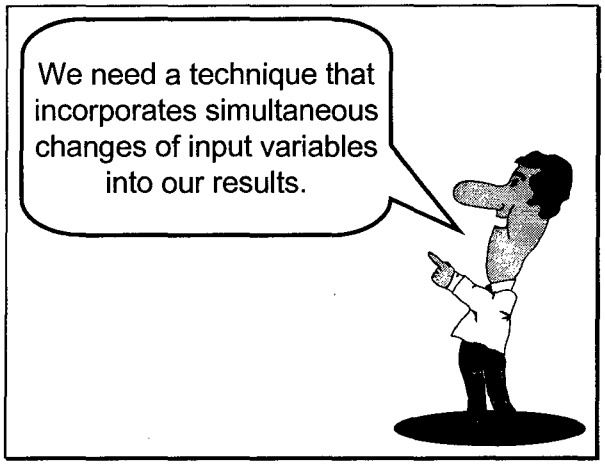
- Advantages
  - Shows effect of changing input variable on outcome
  - Easy to perform

50

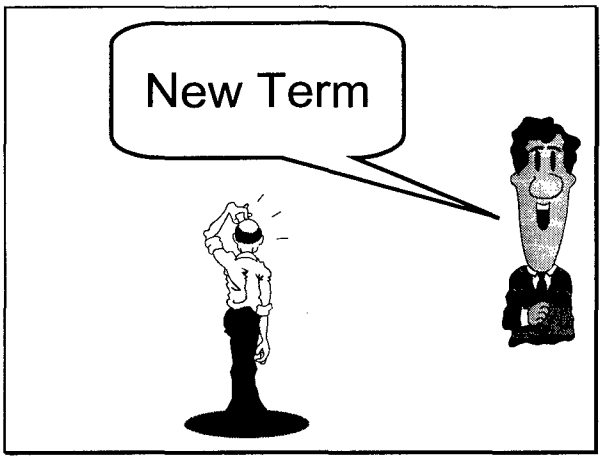
## Sensitivity Analysis

- Disadvantages
  - One input variable changes (others held constant)
  - Limited analysis
  - Does not ...
    - ➡ account for simultaneous change of *ALL* inputs on outcome
    - ➡ account for likelihood of input value actually occurring
    - ➡ reflect reality

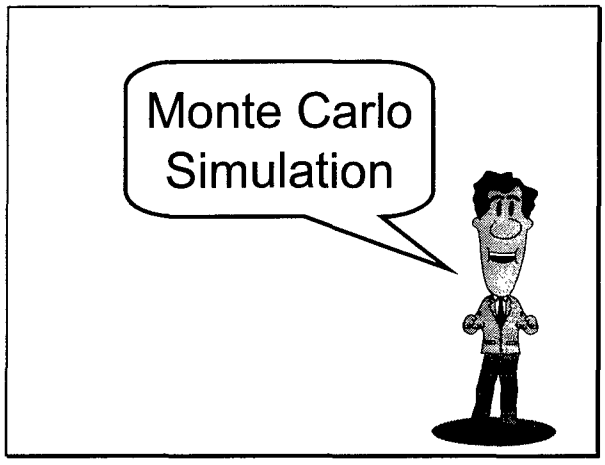
51



52




53




54

## Monte Carlo Simulation

- Input variables described using probability distribution
- Samples randomly drawn from input distributions to calculate results
- Hundreds, even thousands, of samples may be drawn to form a distribution of results

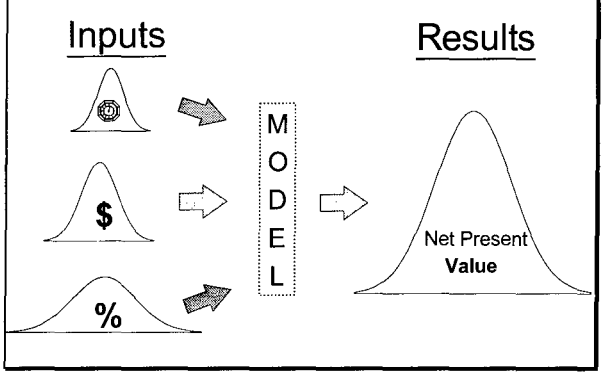
55

## Monte Carlo Con't

- Rigorous extension of ...
  - Best Case
  - Most Likely
  - Worst Case
- Data Input values based on likelihood of occurrence

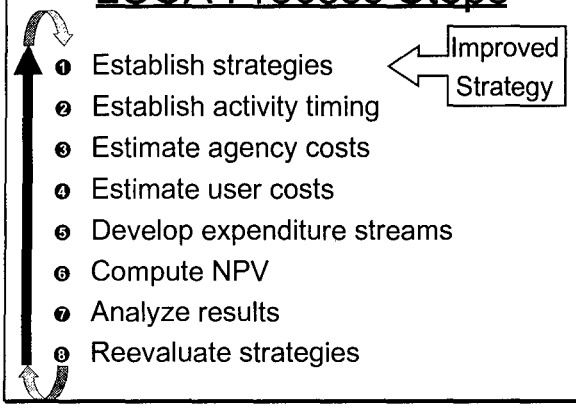
56

## Monte Carlo Simulation




57

## LCCA Process Steps



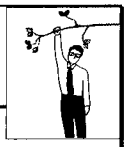
58

## 8. Re-evaluate Strategies

- Modify alternatives
  - ✓Design lives
  - ✓Strengthen shoulders
  - ✓New technologies
- Revise maintenance of traffic plan
  - ✓Reduce construction period
  - ✓Restrict contractor work hours
  - ✓Examine alternative modes of travel

59

## Implications



- Lengths and times of queues
- Agency versus user costs
- Reliability of LCCA outcome
- Practical Realities .....

60

## Practical Realities ...

- Local politics
- Availability of funding
- Industry support to perform the required construction
- Agency experience with a particular strategy
- Accuracy of pavement design and rehabilitation models

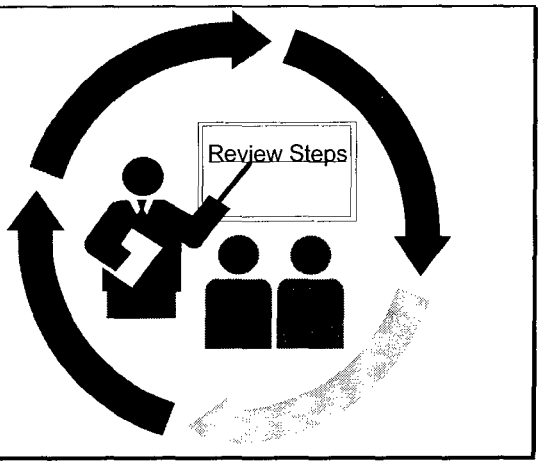
61

## In Closing

LCCA ...

- Decision support tool
- Results are not decisions
- Use process to improve maintenance and rehabilitation strategies
- Logical evaluation process is as important as results

62

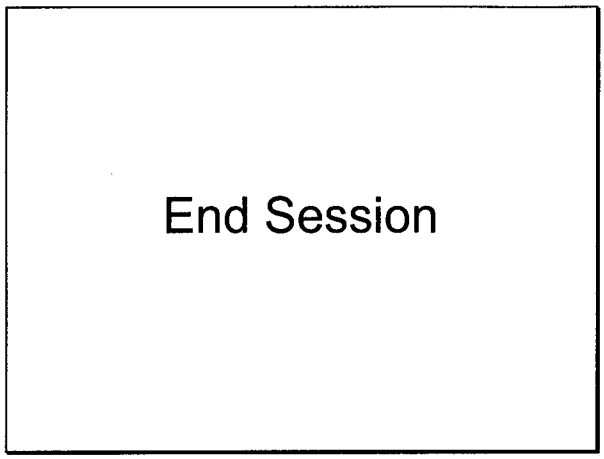



63

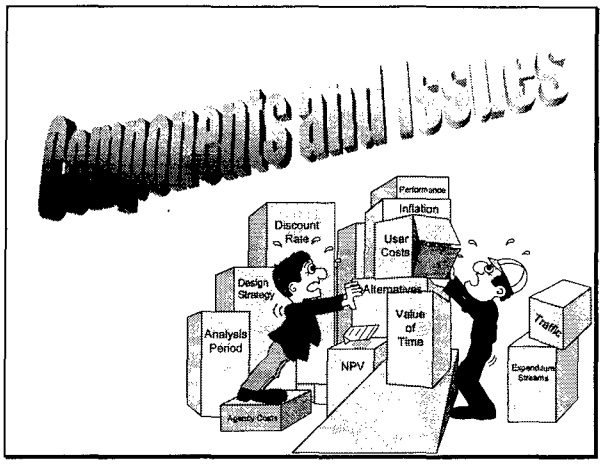
## LCCA Process Steps

1. Establish strategies for analysis period
2. Establish activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure streams
6. Compute NPV
7. Analyze results
8. Reevaluate strategies

64



1




2

## Session Overview

- Analysis periods
- Traffic
- Design strategy
- Performance estimates
- Expenditure streams

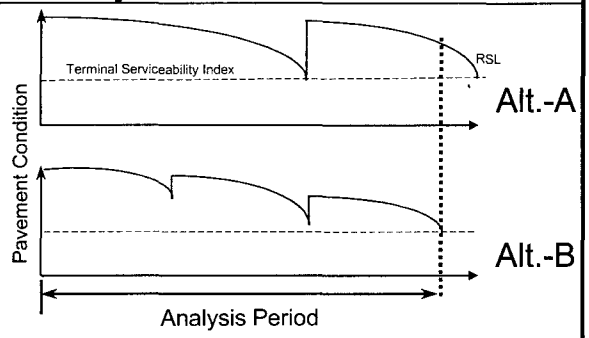
3

## Session Overview Cont'd

- Costing
- Discounting
- Economic indicators
- Agency cost
- User cost

4

## Analysis Period




Include at least one rehabilitation activity.

5

## Analysis Period

- Capture alternative differences
- Include one rehabilitation
- FHWA LCCA Policy
  - Pavements ..... 35 Yrs
  - Bridges..... 75 Yrs

6

## Traffic - Characteristics

- AADT
- Traffic mix
- Growth rates
- Directional hourly volume

7

## Traffic - Projections

- Volumes - User costs
- Classification - User costs
- Load factors - Design
- ESALs - Design

8

## Traffic - Hourly Demand

Sources:

- Traffic data
- Typical default values
  - PennDOT
  - MicroBencost

9

Example

PennDOT AADT Distribution - Hourly Percentages

| | Traffic Pattern Group | | | | | |
|---|---|---|---|---|---|---|
| | Interstate | | Prin. Arterial | | Min. Arterial | |
| Hour | Urban | Rural | Urban | Rural | Urban | Rural |
| 0 - 1 | 1.3 | 1.7 | 0.9 | 0.9 | 0.8 | 0.7 |
| 1 - 2 | 0.9 | 1.4 | 0.5 | 0.5 | 0.4 | 0.4 |
| 2 - 3 | 0.8 | 1.3 | 0.4 | 0.5 | 0.3 | 0.3 |
| 3 - 4 | 0.8 | 1.3 | 0.4 | 0.5 | 0.3 | 0.4 |
| 4 - 5 | 1.1 | 1.4 | 0.6 | 0.9 | 0.4 | 0.8 |
| 5 - 6 | 2.1 | 2.1 | 1.8 | 2.3 | 1.3 | 2.2 |
| 6 - 7 | 4.7 | 3.7 | 4.4 | 4.9 | 4.0 | 4.5 |
| 7 - 8 | 6.4 | 4.9 | 6.2 | 6.2 | 6.4 | 5.5 |
| 8 - 9 | 5.6 | 4.9 | 5.7 | 5.5 | 5.7 | 5.3 |
| 9 - 10 | 5.1 | 5.2 | 5.1 | 5.3 | 4.8 | 5.4 |
| 10 - 11 | 5.2 | 5.5 | 5.2 | 5.4 | 4.9 | 5.8 |
| 11 - 12 | 5.4 | 5.8 | 5.6 | 5.6 | 5.5 | 6.0 |
| | | | | | | |
| 23 - 24 | 2.0 | 2.4 | 1.7 | 1.5 | 1.6 | 1.4 |

10

## Performance Estimates

- Performance periods affect timing of rehabilitation
  - Frequency
  - Expenditure timing
  - Traffic levels
  - User costs

11

## Design Strategy

- Initial design
- Identify supporting rehabs
- Viable and competitive

12

## PCC Design Strategy

| | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| Activity | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| ■ Clean and Seal Joints | X | X | X | X | X | X | |
| ■ Seal Coat Shoulders | X | X | X | X | X | | X |
| ■ CPR - Patch | | | | X | | X | |
| - Spall Repair | | | | X | | | |
| - Slab Stabilization | | | | X | | | |
| - Diamond Grinding | | | | X | | | |
| ■ Overlay | | | | | | X | |
| ■ Saw and Seal Joints | | | | | | X | |
| ■ Pave Shoulders | | | | | | X | |
| ■ Adjust Guard Rail and Drainage Structures | | | | | | X | |

13

## Example

- 6 Lane Facility (3 Lane per dir.)
- Work Zone 1 Lane Open
- 30 Year Analysis Period
- Initial AADT = 110,000 vpd
- 2 Rehabs including maint. plan

14

## Options ....

- Plan to add capacity in the outyears
- Strengthen shoulders
- Examine use of alternative routes, modes of transportation

15

## Options Cont'd

- Use materials with greater performance lives thereby reducing number of rehabs
- Initiate programs, such as preventive maintenance, that preserve pavement life

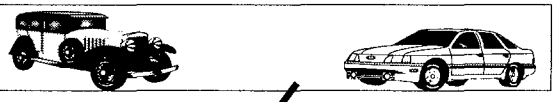
16

## Costing and Discounting

- Costing - Type of Dollars
  - Constant (real)
  - Inflated (nominal)

17

### Can You Assume Inflation?



1947 1997

Top-selling car

$8,890 (Chevrolet) $18,545 (Ford Taurus)

Average time to earn that much

4.8 months 5.3 months

Gallon of gas

$1.70 $1.22

1997 $Dollars$

18

## Example: Deflation

Computer Cost:

- 1989 - $2,500
- 1998 - $1,200

19

## Costing and Discounting

- Costing - Type of Dollars
  - Constant (real)
  - Inflated (nominal)
- Discounting - Type of Rates
  - Real
  - Nominal

20

## Discounting - Rate Factors

- 4.0% - Real
- 3.5% - Inflation
- 4.0% - Risk premium

---

- 11.5% - Nominal

21

## Discounting - Matching Dollars & Rates

- Real dollars and rates
- Nominal dollars and rates
- Never mix nominal and real

22

## Discounting "True-isms"

- Present costs valued higher
- Out year costs worth less

23

## Discounting "True-isms"

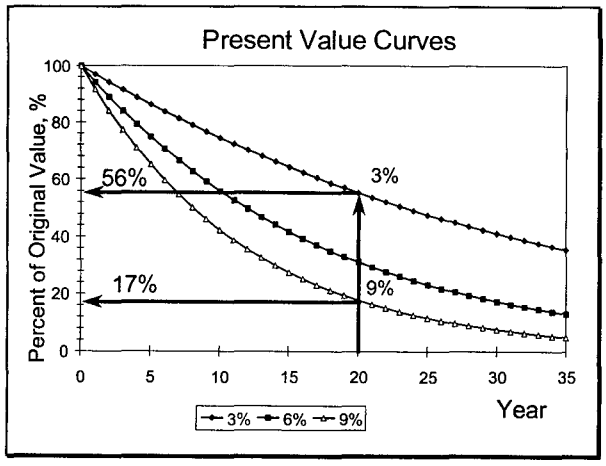
- Low Rates -

  Favor alternatives with higher initial costs and lower future costs

- High Rates -

  Favor alternatives with lower initial costs and higher future costs

24



25

## Discount Rate Selection

- Opportunity Cost
- Office of Management and Budget Circular A-94

26

## Opportunity Cost - Personal

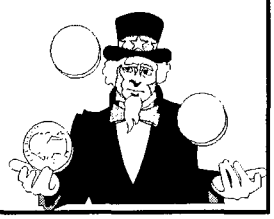
| | |
|---|---|
| ■ 401K - IRA | 28% - 35%+ |
| ■ Credit Cards | 15% - 22% |
| ■ Signature Loans | 12% - 15% |
| ■ Car Loans | 8% - 12% |
| ■ Home Equity | 7% - 11% |
| ■ Mortgage | 5% - 8% |
| ■ Savings/Checking | 0% - 3% |

Nominal rates of return

27

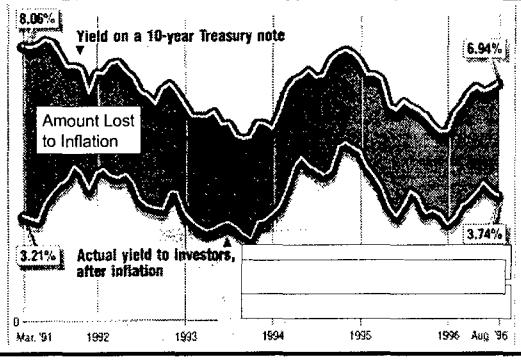
## Opportunity Cost - Gov't

- J. "Queue" Public
- Other Investments
- Old Bonds
- New Bonds



28

## Real Discount Rate




29

## Real Discount Rates
### Source: OMB Circular A-94

| | Investment Maturity | | | | |
|---|---|---|---|---|---|
| YEAR | 3 | 5 | 7 | 10 | 30 |
| Nov 92 | 2.7 | 3.1 | 3.3 | 3.6 | 3.8 |
| Feb 93 | 3.1 | 3.6 | 4.0 | 4.3 | 4.5 |
| Feb 94 | 2.1 | 2.3 | 2.5 | 2.7 | 2.8 |
| Feb 95 | 4.2 | 4.5 | 4.6 | 4.8 | 4.9 |
| Feb 96 | 2.7 | 2.7 | 2.8 | 2.8 | 3.0 |
| Feb 97 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 |
| Jan 98 | 3.4 | 3.5 | 3.5 | 3.6 | 3.8 |
| Avg | 3.1 | 3.3 | 3.4 | 3.6 | 3.8 |
| Std | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 |

(No Inflation Premium)

30

## Circular A-94

### Discount Rates Web Address:

http://www.whitehouse.gov/WH/EOP/OMB/html/circulars/

Select A-94 and see appendix C.

31

## Recommend

- 3 to 5 %
- Real rates with real dollars

32

## Economic Indicators

- Internal rate of return
- Benefit cost ratio
- Equivalent uniform annual costs
- Net present value

33

## Economic Indicator of Choice

Net
Present
Value

34

## Agency Costs

- Design and Engineering
- Initial Construction
- Maintenance of Traffic
- Preventive Maintenance
- Rehabilitation
- Reactive Maintenance/Operating Cost

Salvage Value Sunk Costs

35

## Salvage Value

- Remaining service life
  - % of last rehab cost
- Residual value
  - Value of recycled material

36

## Sunk Costs

... costs that are not relevant to the decision at hand

37

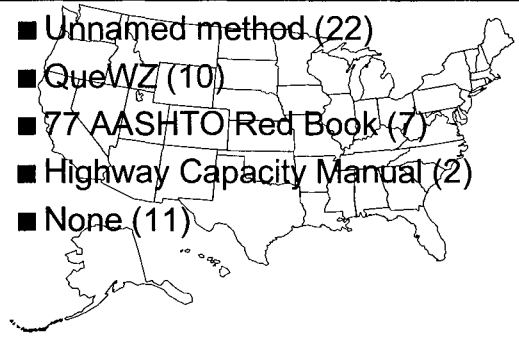
## User Costs: 2B or not 2B

- Pro - User costs drive transportation investments.
  - User fees collected for public investment
- Con - Can't recoup costs
  - "Not in my budget"

38

## AASHTO User Cost Survey for Innovative Contracting

- Unnamed method (22)
- QueWZ (10)
- 77 AASHTO Red Book (7)
- Highway Capacity Manual (2)
- None (11)



39

## User Cost Components

- Vehicle crash cost
- Vehicle operating cost
- User delay

40

## User Cost Components

- Vehicle crash cost
  - Property damage only - $
  - Injury - $$
  - Fatality - $$$$$
- Data sources

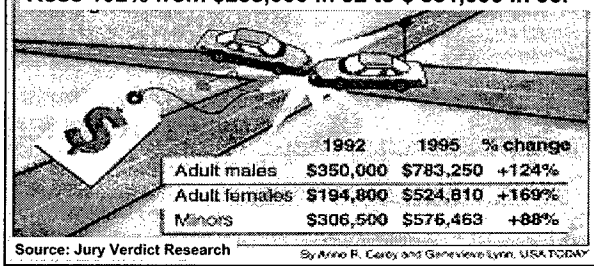
41

**USA SNAPSHOTS®**

A look at statistics that shape the nation

**Higher Traffic Fatality Awards**

**Median Jury Awards for all Traffic Crash Fatalities Rose 102% from $288,000 in 92 to $ 581,000 in 95.**



| | 1992 | 1995 | % change |
|---|---|---|---|
| Adult males | $350,000 | $783,250 | +124% |
| Adult females | $194,800 | $524,810 | +169% |
| Minors | $306,500 | $576,463 | +88% |

Source: Jury Verdict Research

By Anne R. Carey and Genevieve Lynn, USA TODAY

42

## User Cost Components

- Vehicle crash cost
- Vehicle operating cost
  - Normal operations
  - Work zone

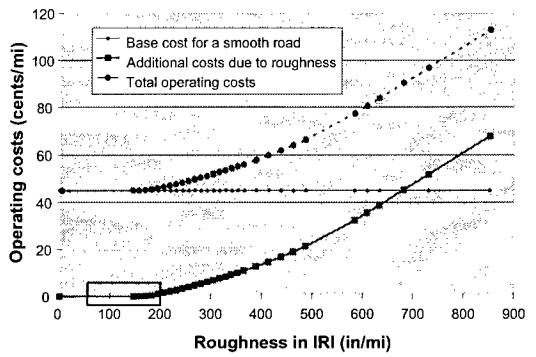
43

## VOC Normal Operations

- Function of ...
  - Pavement performance
  - VOC - IRI relationship
- May be significant but ...
  ..Not quantifiable at this time

44

**Effect of Roughness on Road User Costs in New Zealand**




45

## VOC in Work Zones

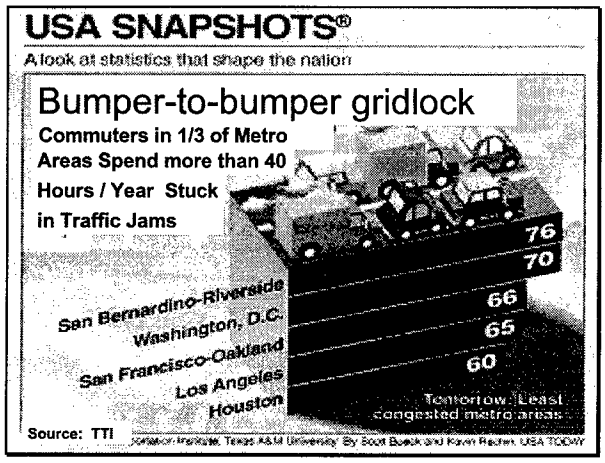
- Speed change cost
- Stopping cost
- Idling cost

46

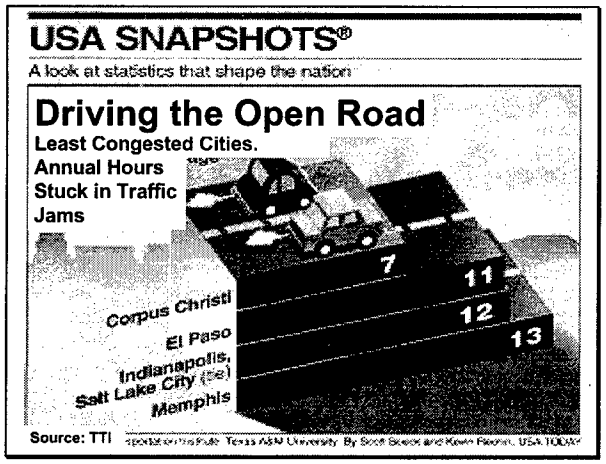
## User Cost Components

- Vehicle crash cost
- Vehicle operating cost
- User delay
  - WZ reduced speed delay
  - Congestion delay

47




48



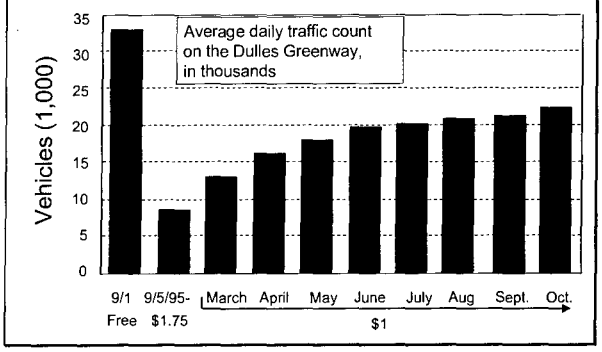
49

## Value of Time: Sources

- A + B Bidding - Lane rentals
- Toll facilities
- Congestion pricing
- High Occupancy Toll (HOT)
- US DOT - FHWA HERS
- Research studies

50

## Toll Facilities




51

## Congestion Pricing

- Houston 1990
- Hardy toll road experiment
- $1.00 peak - $.50 off peak
- Too successful
- Lost $500,000 in 90 days

52

## HOT Lanes

- San Diego I-15
  - $10 Million experiment 12/96
  - Started at $50/mo., now at $70
  - 700 permits with 400 waiting
- Orange Co - Riverside Freeway
  - $2.25 saves 20 minutes

53

## HOT Lanes Cont'd

- Houston Katy Freeway
  - 2 for 3 @ $2.00

54

## Value of Time (USDOT 1997)

| | | $ / Person Hour | | | |
|---|---|---|---|---|---|
| Travel Category | | Local | | Inter City | |
| | | Low | High | Low | High |
| AUTO | Business | 15.00 | 22.60 | 15.00 | 22.60 |
| AUTO | Personal | 6.00 | 10.20 | 10.20 | 15.30 |
| AUTO | Mixed | 6.40 | 10.70 | 10.40 | 15.70 |
| Trucks | | 16.50 | 16.50 | 16.50 | 16.50 |

1995 Dollars

55

## Value of Time (HERS 1997)

Source: Highways Economic Requirement System 9/97

| Travel Category | $ / Veh. Hour | | |
|---|---|---|---|
| | | Trucks | |
| | Autos | Single Unit | Combination |
| Business | 28 | 26 | 31 |
| Personal | 13 | NA | NA |
| % AADT Personal | 90% | 0% | 0% |
| Wt. Avg. | 14 | 26 | 31 |

1995 Dollars

56

## Value of Time (Research Studies)

1996 Dollars

| Vehicle Class | $ / Vehicle Hour Value |
|---|---|
| Passenger Vehicles | 11.58 |
| Single Unit Trucks | 18.54 |
| Combination Trucks | 22.31 |

Average of ...
AASHTO Red Book and MicroBENCOST Default Values

57

## Value of Time Recommendations

| Vehicle Class | $ / Vehicle Hour Range |
|---|---|
| Passenger Vehicles | 10.00 - 13.00 |
| Single Unit Trucks | 17.00 - 20.00 |
| Combination Trucks | 21.00 - 24.00 |

1996 Dollars

58

## Further Information ...

LCCA Tech Bulletin ...

- Fundamental principles
- Good practice
- LCCA issues
- Case studies
- Uncertainty and variability
- Computer software

59

## Parting Caveat

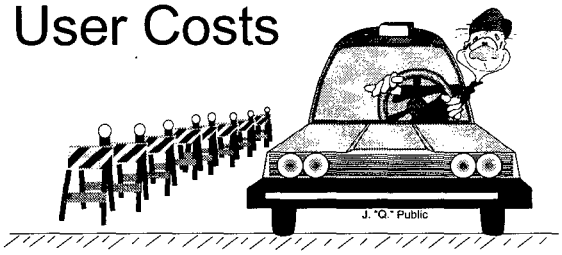
- Defending LCCA results
  - Justify all assumptions
  - Address all issues (even if not relevant to the analysis at hand)

60

## End Session

1

# Introduction to Project Level User Costs




2

## Session Overview

- Components
- Operating Conditions
- Work zone

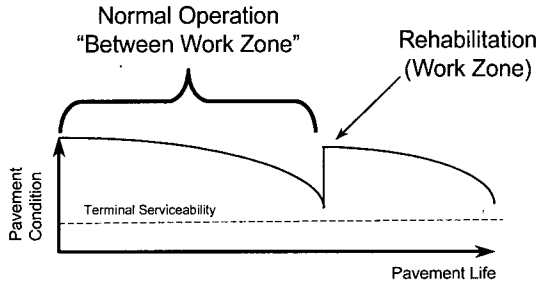
3

## User Cost Components

- Vehicle operating
- User delay
- Circuity
- Crash

4

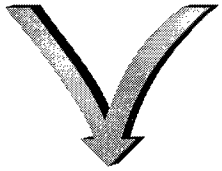
## Operating Conditions




5

## Our Primary Focus ...

Vehicle Operating User Delay



Crash Costs

Work Zone

6

## WZ User Costs Function of ...

- Type
- Characteristics
- Duration
- Frequency
- Timing
- Traffic Operations

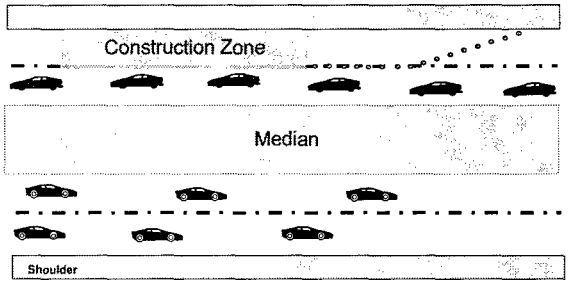
7

## Work Zone Types

- Road closures
- Single lane closure
- Two lane two way operation

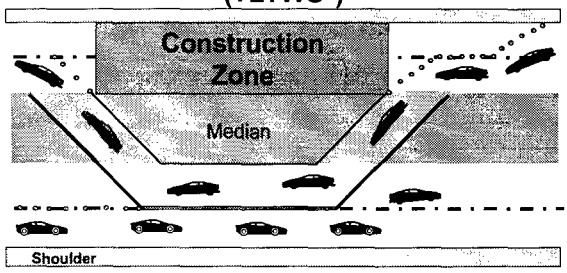
8

## Single Lane Closure (SLC)




9

## Two Lane Two Way Operation (TLTWO*)




*Also called "Crossover" or "Head to Head"

10

## WZ Characteristics

- Length
- Posted Speed
- Hours of Operation
- Capacity
- Alternate Routes/Detours

11

## Work Zone Duration

Includes:

- Hours per day
- Number of days

12

## Work Zone Frequency

- Number of times rehab work zones need to be established over the analysis period
- The more rehabilitations the more work zones

13

## Work Zone Timing

- Refers to the year the work zone is in place
- Impacts user cost NPV
  - Out-year traffic levels
  - Discount factor

14

## Net Present Value (NPV)

$$NPV = \text{Initial Cost} + \sum_{k=1}^{N} \text{Future Cost}_k \times \underbrace{\left[\frac{1}{(1+I)^{n_k}}\right]}_{\text{Present Value Factor}}$$

I = discount rate
n = year of expenditure

15

## Work Zone Analysis

- Different work zone types must be analyzed separately.
- Work zones with different characteristics, including traffic demand, must also be analyzed separately.

16

## Work Zone Analysis Con't

- Manual approach
  - Capacity analysis
  - AASHTO Red Book
- Automated programs
  - MicroBenCost
  - QueWZ

17

## McTrans Ph: **1-800-226-1013**

- MicroBenCost: ~ $110
- QueWZ: ~ $20

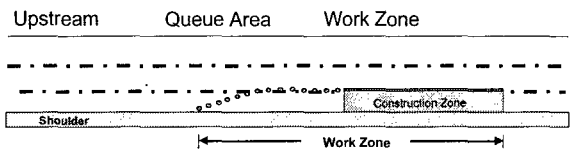
Includes: software, documentation, and shipping

18

## Work Zone Traffic Operations

19

## Work Zone Layout




20

## WZ Operations

- Free Flow (Base Case)
  WZ Capacity Exceeds Demand
- Forced Flow (Congestion)
  Demand Exceeds WZ Capacity

21

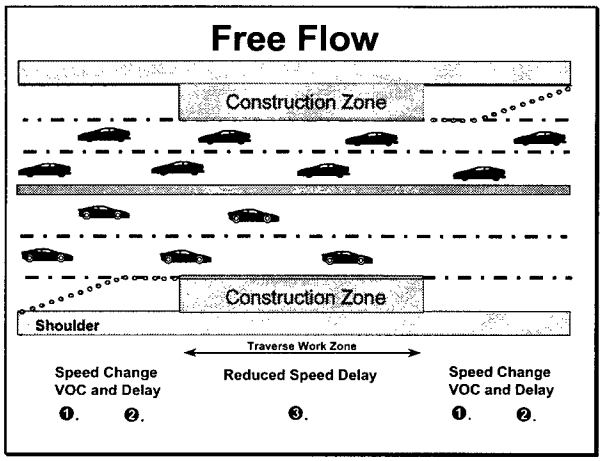
## Free Flow Cost Components

WZ capacity not exceeded ...

➡ Speed change costs
  ❶ VOC
  ❷ Delay

➡ Reduced speed costs
  ❸ Delay

22



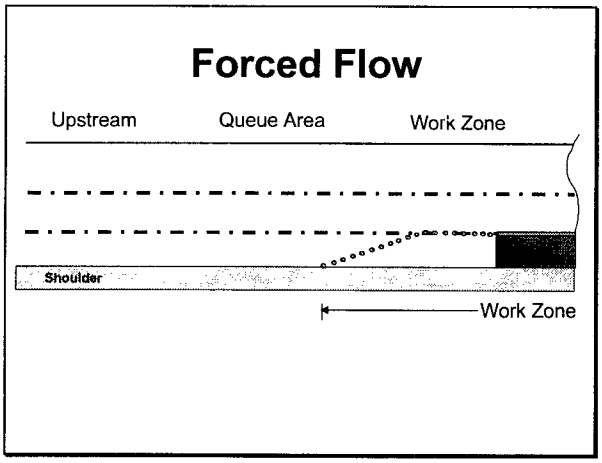

23

## Forced Flow Cost Components

WZ capacity exceeded ...

- ➡ Stopping cost
  - ❹ VOC
  - ❺ Delay
- ➡ Queuing costs
  - ❻ Idling
  - ❼ Delay

24



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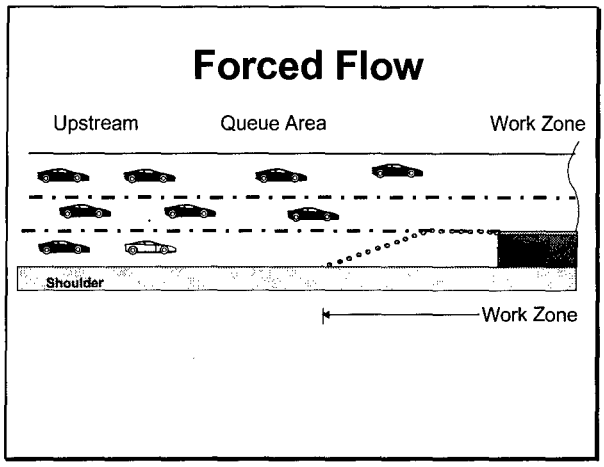
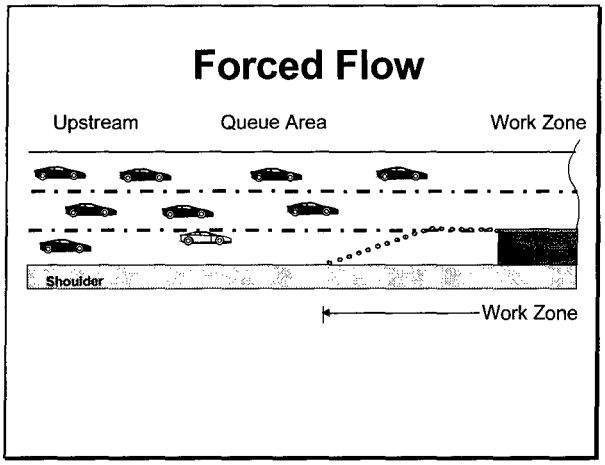
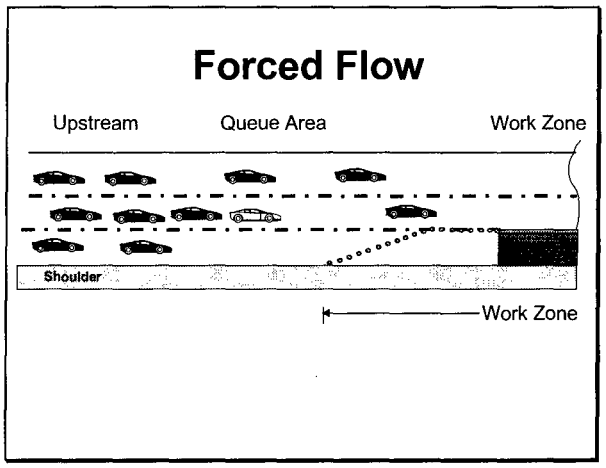

Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

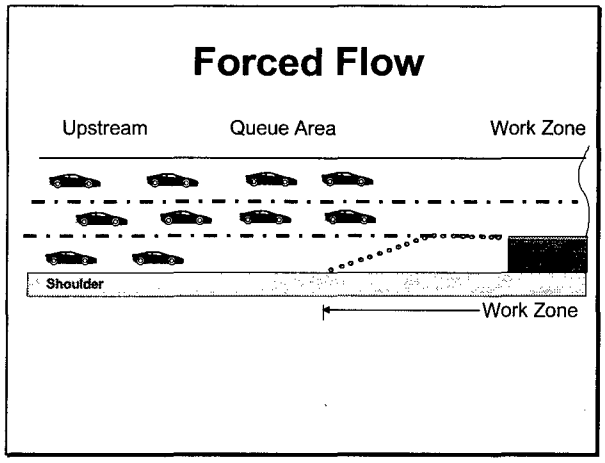
26


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

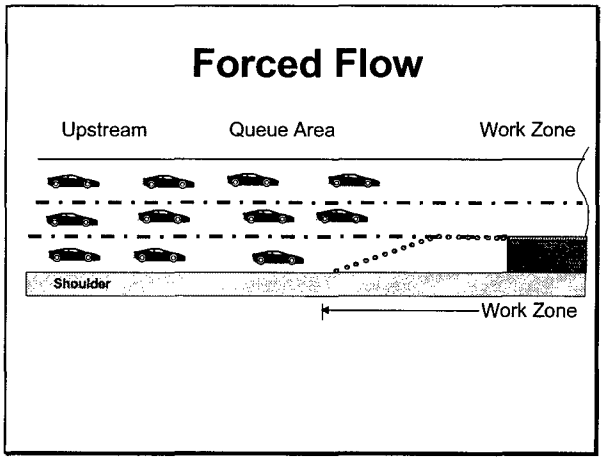
27


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

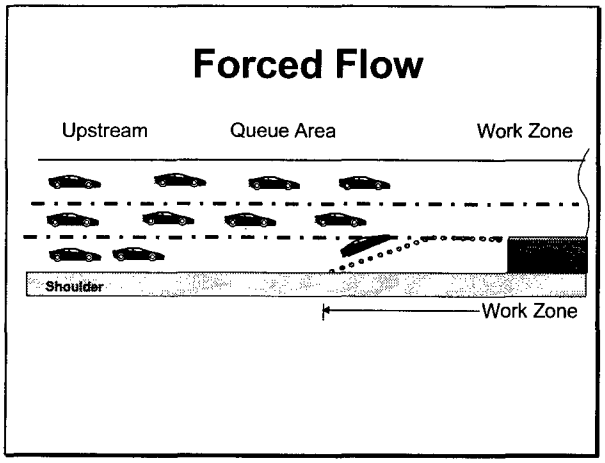
28


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

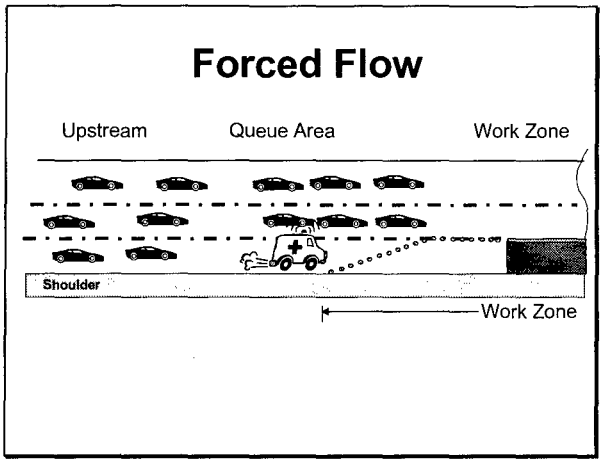
29


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

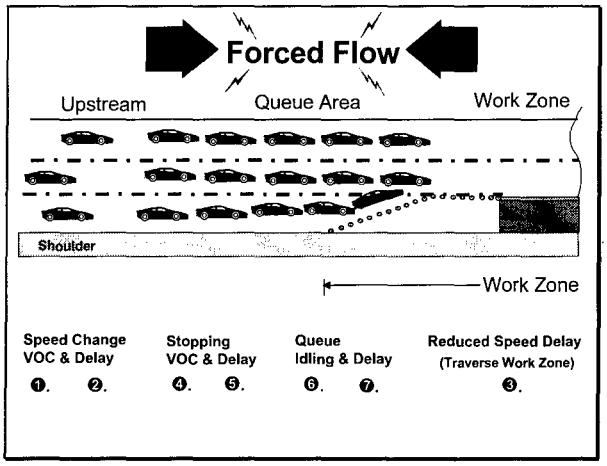
30


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

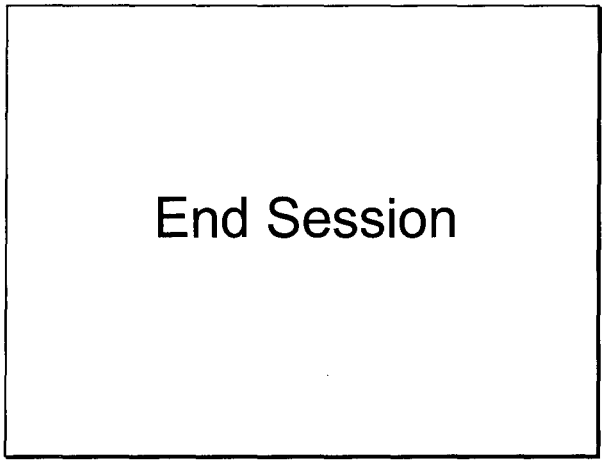
31


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone

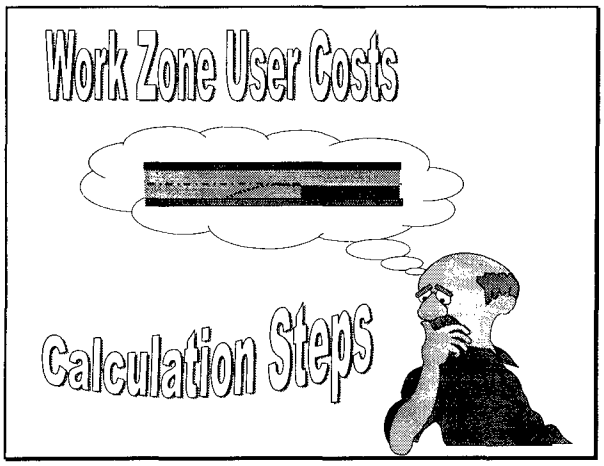
32


Forced Flow
Upstream
Queue Area
Work Zone
Shoulder
Work Zone
Speed Change
VOC & Delay
❶. ❷.
Stopping
VOC & Delay
❹. ❺.
Queue
Idling & Delay
❻. ❼.
Reduced Speed Delay
(Traverse Work Zone)
❸.

33


End Session

1




2

## WZ User Costs Steps

1. Determine Capacity
2. Calculate Directional Hourly Demand
3. Identify User Cost Components
4. Quantify Traffic Affected by each Component
5. Compute Reduced Speed Delay
6. Assign VOC Cost Rates

(More)

3

## WZ User Costs Steps (Cont'd)

7. Assign Delay Cost Rates
8. Assign Traffic to Vehicle Classes
9. Compute User Costs by Vehicle Class
10. Determine Circuity
11. Compute Crash Costs
12. Sum Total User Costs

4

## 1. Determine Capacity

- With and without WZ
- Resources:
  - Research Studies
  - Highway Capacity Manual

5

## Free Flow Capacity

- Ideal
  - 2200 to 2300 pvplph
- Mixed flow reductions
  - Trucks present
  - Lane width
  - Hazard offset
  - Recreational drivers

6

## Mixed Traffic Capacity

1000 - 2300 vplph

See Table 3.4-3.6 of Technical Bulletin

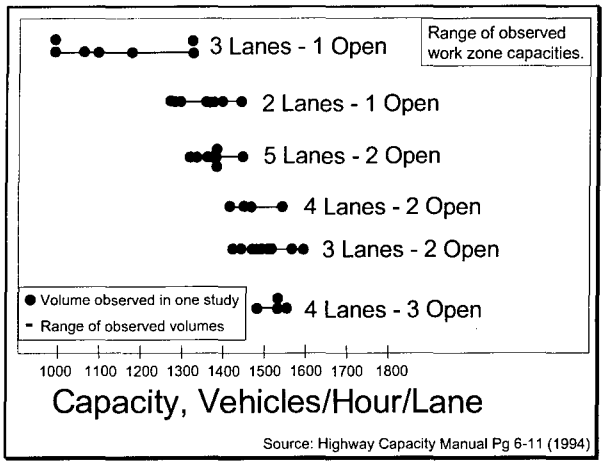
7

## Work Zone Capacity

| Directional Lanes | | | | |
|---|---|---|---|---|
| Normal Operations | WorkZone Operations | No of Studies | Capacity (vph) | Capacity (Veh/Ln-Hr.) |
| 3 | 1 Open | 7 | 1170 | 1170 |
| 2 | 1 Open | 8 | 1340 | 1340 |
| 5 | 2 Open | 8 | 2740 | 1370 |
| 4 | 2 Open | 4 | 2960 | 1480 |
| 3 | 2 Open | 9 | 2980 | 1490 |
| 4 | 3 Open | 4 | 4560 | 1520 |

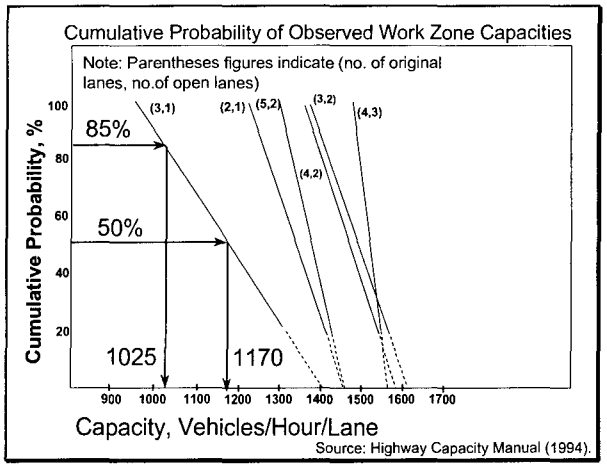
Source: 1994 Highway Capacity Manual - Table 6.1

8




Source: Highway Capacity Manual Pg 6-11 (1994)

9




Source: Highway Capacity Manual (1994).

10

## Queue Dissipation Cap.

- Has significant impact on time to clear queue
- Ranges from 1500 to 2000 vphpl
- See HCM Page 2-32

11

## 2. Calculate Directional Hrly Demand

Directional Hourly Demand =

- (AADT) x
- (% Hourly Demand) x
- (Directional Factor)

12

## Sources

- AADT & directional factor
  - Traffic counts
- Hourly distributions
  - MicroBENCOST
  - Traffic counts

**13**

Rural Default Hourly Distributions, MicroBenCost

| | Interstate | | | Principal Arterials | | | Minor Arterials | | | Major Collectors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | Direction | | % | Direction | | % | Direction | | % | Direction | |
| Hour | ADT | In | Out | ADT | In | Out | ADT | In | Out | ADT | In | Out |
| 0 - 1 | 1.8 | 48 | 52 | | | | | | | | | |
| 1 - 2 | 1.5 | 48 | 52 | | | | | | | | | |
| 2 - 3 | 1.3 | 45 | 55 | | | | | | | | | |
| 3 - 4 | 1.3 | 53 | 47 | | | | | | | | | |
| 4 - 5 | 1.5 | 53 | 47 | | | | | | | | | |
| 5 - 6 | 1.8 | 53 | 47 | | | | | | | | | |
| 6 - 7 | 2.5 | 57 | 43 | **Same** | | | **Same** | | | **Same** | | |
| 7 - 8 | 3.5 | 56 | 44 | | | | | | | | | |
| 8 - 9 | 4.2 | 56 | 44 | | | | | | | | | |
| 9 - 10 | 5.0 | 54 | 46 | | | | | | | | | |
| 10 - 11 | 5.4 | 51 | 49 | | | | | | | | | |
| 11 - 12 | 5.6 | 51 | 49 | | | | | | | | | |
| ⋮ | | ⋮ | | | | | | | | | | |

**14**

Rural Default Hourly Distributions Con't, MicroBenCost

| | Interstate | | | Principal Arterials | | | Minor Arterials | | | Major Collectors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | Direction | | % | Direction | | % | Direction | | % | Direction | |
| Hour | ADT | In | Out | ADT | In | Out | ADT | In | Out | ADT | In | Out |
| 12 - 13 | 5.7 | 50 | 50 | | | | | | | | | |
| 13 - 14 | 6.4 | 52 | 48 | | | | | | | | | |
| 14 - 15 | 6.8 | 51 | 49 | | | | | | | | | |
| 15 - 16 | 7.3 | 53 | 47 | | | | | | | | | |
| 16 - 17 | 9.3 | 49 | 51 | | | | | | | | | |
| 17 - 18 | 7.0 | 43 | 57 | | | | | | | | | |
| 18 - 19 | 5.5 | 47 | 53 | **Same** | | | **Same** | | | **Same** | | |
| 19 - 20 | 4.7 | 47 | 53 | | | | | | | | | |
| 20 - 21 | 3.8 | 46 | 54 | | | | | | | | | |
| 21 - 22 | 3.2 | 48 | 52 | | | | | | | | | |
| 22 - 23 | 2.6 | 48 | 52 | | | | | | | | | |
| 23 - 24 | 2.3 | 47 | 53 | | | | | | | | | |

**15**

Example

PennDOT AADT Distribution - Hourly Percentages

| | Traffic Pattern Group | | | | | |
|---|---|---|---|---|---|---|
| | Interstate | | Prin. Arterial | | Min. Arterial | |
| Hour | Urban | Rural | Urban | Rural | Urban | Rural |
| 0 - 1 | 1.3 | 1.7 | 0.9 | 0.9 | 0.8 | 0.7 |
| 1 - 2 | 0.9 | 1.4 | 0.5 | 0.5 | 0.4 | 0.4 |
| 2 - 3 | 0.8 | 1.3 | 0.4 | 0.5 | 0.3 | 0.3 |
| 3 - 4 | 0.8 | 1.3 | 0.4 | 0.5 | 0.3 | 0.4 |
| 4 - 5 | 1.1 | 1.4 | 0.6 | 0.9 | 0.4 | 0.8 |
| 5 - 6 | 2.1 | 2.1 | 1.8 | 2.3 | 1.3 | 2.2 |
| 6 - 7 | 4.7 | 3.7 | 4.4 | 4.9 | 4.0 | 4.5 |
| 7 - 8 | 6.4 | 4.9 | 6.2 | 6.2 | 6.4 | 5.5 |
| 8 - 9 | 5.6 | 4.9 | 5.7 | 5.5 | 5.7 | 5.3 |
| 9 - 10 | 5.1 | 5.2 | 5.1 | 5.3 | 4.8 | 5.4 |
| 10 - 11 | 5.2 | 5.5 | 5.2 | 5.4 | 4.9 | 5.8 |
| 11 - 12 | 5.4 | 5.8 | 5.6 | 5.6 | 5.5 | 6.0 |
| ⋮ | | ⋮ | | ⋮ | | ⋮ |

16

Example

PennDOT AADT Distribution - Hourly Percentages

| | Traffic Pattern Group | | | | | |
|---|---|---|---|---|---|---|
| | Interstate | | Prin. Arterial | | Minor Arterial | |
| Hour | Urban | Rural | Urban | Rural | Urban | Rural |
| 12 - 13 | 5.5 | 5.7 | 6.0 | 5.7 | 6.0 | 6.2 |
| 13 - 14 | 5.5 | 5.9 | 5.9 | 5.9 | 5.7 | 6.4 |
| 14 - 15 | 6.1 | 6.3 | 6.4 | 6.6 | 6.3 | 7.2 |
| 15 - 16 | 7.3 | 6.9 | 7.4 | 7.7 | 7.6 | 8.1 |
| 16 - 17 | 7.8 | 7.2 | 7.8 | 8.0 | 8.3 | 8.0 |
| 17 - 18 | 7.2 | 6.6 | 7.5 | 7.4 | 8.0 | 7.1 |
| 18 - 19 | 5.4 | 5.3 | 5.9 | 5.5 | 6.2 | 5.4 |
| 19 - 20 | 4.3 | 4.4 | 4.8 | 4.3 | 5.1 | 4.4 |
| 20 - 21 | 3.7 | 3.8 | 4.0 | 3.6 | 4.3 | 3.6 |
| 21 - 22 | 3.2 | 3.4 | 3.3 | 3.0 | 3.4 | 2.9 |
| 22 - 23 | 2.6 | 2.9 | 2.4 | 2.3 | 2.4 | 2.1 |
| 23 - 24 | 2.0 | 2.4 | 1.7 | 1.5 | 1.6 | 1.4 |

17

## 3. Identify User Cost Components

- ➡ Free Flow
  - Speed Change
  - Reduced Speed

- ➡ Forced Flow
  - Stopping
  - Queuing

18

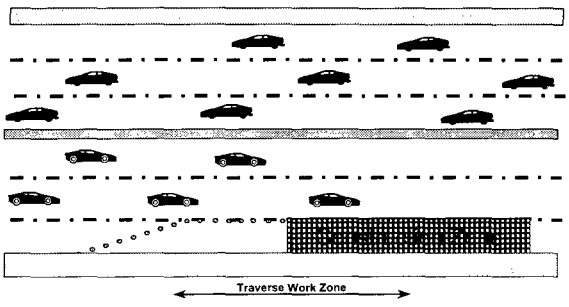
## Free Flow Cost Components

WZ capacity not exceeded ...

- ➡ Speed change costs
  - ❶ Delay
  - ❷ VOC
- ➡ Reduced speed costs
  - ❸ Delay

19

## Free Flow




20

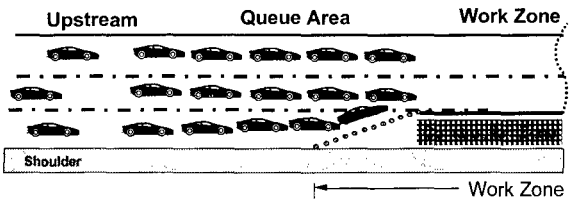
## Forced Flow Cost Components

WZ capacity exceeded ...

- ➡ Stopping cost
  - ❹ Delay
  - ❺ VOC
- ➡ Queuing costs
  - ❻ Delay
  - ❼ Idle

21

## Forced Flow



22

## 4. Quantify Traffic Affected by Each Component

- Lane closure hours
- 24 Hours analysis period

23

## Example

- AADT = 67,406 veh per day. (SouthBound)
- Traff. Mix 90% Auto, 5.4% SU, 4.6% Combo
- 3 Lane Open Non Work Zone (Cap. 6285 vph)
- 2 Lane Open - 1 Lane Closed for Work Zone (Cap. 3027 vph)
- Work Zone Hours 8 pm - 5 am, 9 am - 3 pm
- Length = 5.25 miles
- Approach Speed = 55 mph
- Work Zone Speed = 40 mph
- Work Zone In Place 60 Days

24

## Twenty Four Hour Analysis Period - SouthBound

| Hour | Hourly Distr. (%) | **Demand** (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ @40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e_i+f_{i-1})$ | IF f > 0,c,0 | See Note** | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 0 - 1 | 0.9 | 607 | 3,027 | (2,420) | 0 | 0 | 607 | 607 |
| 1 - 2 | 0.5 | 337 | 3,027 | (2,690) | 0 | 0 | 337 | 337 |
| 2 - 3 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 3 - 4 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 4 - 5 | 0.6 | 404 | 3,027 | (2,623) | 0 | 0 | 404 | 404 |
| 5 - 6 | 1.8 | 1,213 | 6,285 | (5,072) | 0 | 0 | 0 | 0 |
| 6 - 7 | 4.4 | 2,966 | 6,285 | (3,319) | 0 | 0 | 0 | 0 |
| 7 - 8 | 6.2 | 4,179 | 6,285 | (2,106) | 0 | 0 | 0 | 0 |
| 8 - 9 | 5.7 | 3,842 | 6,285 | (2,443) | 0 | 0 | 0 | 0 |
| 9 - 10 | 5.1 | 3,438 | 3,027 | 411 | 411 | 3,438 | 3,027 | 0 |
| 10 - 11 | 5.2 | 3,505 | 3,027 | 478 | 889 | 3,505 | 3,027 | 0 |
| 11 - 12 | 5.6 | 3,775 | 3,027 | 748 | 1,637 | 3,775 | 3,027 | 0 |
| ° | ° | ° | ° | ° | ° | ° | ° | ° |
| ° | ° | ° | ° | ° | ° | ° | ° | ° |
| ° | ° | ° | ° | ° | ° | ° | ° | ° |

** If(d=3027,If (c>d,d,c),0)

25

# Table Continued

| Hour | Hourly Distr. (%) | **Demand** (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ at 40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e_i+f_{i-1})$ | IF f > 0,c,0 | See Note** | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 12 - 13 | 6.0 | 4,044 | 3,027 | 1,017 | 2,654 | 4,044 | 3,027 | 0 |
| 13 - 14 | 5.9 | 3,977 | 3,027 | 950 | 3,604 | 3,977 | 3,027 | 0 |
| 14 - 15 | 6.4 | 4,314 | 3,027 | 1,287 | 4,891 | 4,314 | 3,027 | 0 |
| 15 - 16 | 7.4 | 4,988 | 5,454 | (466) | 4,425 | 4,988 | 0 | 0 |
| 16 - 17 | 7.8 | 5,258 | 5,454 | (196) | 4,229 | 5,258 | 0 | 0 |
| 17 - 18 | 7.5 | 5,055 | 5,454 | (399) | 3,830 | 5,055 | 0 | 0 |
| 18 - 19 | 5.9 | 3,977 | 5,454 | (1,477) | 2,353 | 3,977 | 0 | 0 |
| 19 - 20 | 4.9 | 3,303 | 5,454 | (2,151) | 202 | 3,303 | 0 | 0 |
| 20 - 21 | 4.0 | 2,696 | 3,027 | (331) | 0 | **1,646** * | 2,898 | **1,051** |
| 21 - 22 | 3.3 | 2,224 | 3,027 | (803) | 0 | 0 | 2,224 | 2,224 |
| 22 - 23 | 2.4 | 1,618 | 3,027 | (1,409) | 0 | 0 | 1,618 | 1,618 |
| 23 - 24 | 1.7 | 1,146 | 3,027 | (,1881) | 0 | 0 | 1,146 | 1,146 |
| | | | | | Total | **47,279** | **27,936** | **7,926** |

*Prorated based on portion of hour required to clear queue.

26

## Traffic Affected - Free Flow

- Speed Change (55-40-55)
  - 7,926 vpd (60 days) = 475,569 veh.
- Traverse Workzone
  (at reduced speed of 40 mph)
  - 27,936 vpd (60 days) = 1,676,152 veh.

27

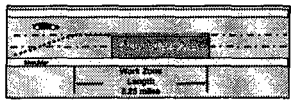
## Traffic Affected - Forced Flow

- Stopping (55-0-55)
  - 47,279 vpd (60 day) = 2,836,762 veh.
- Queuing
  - Same as above

28

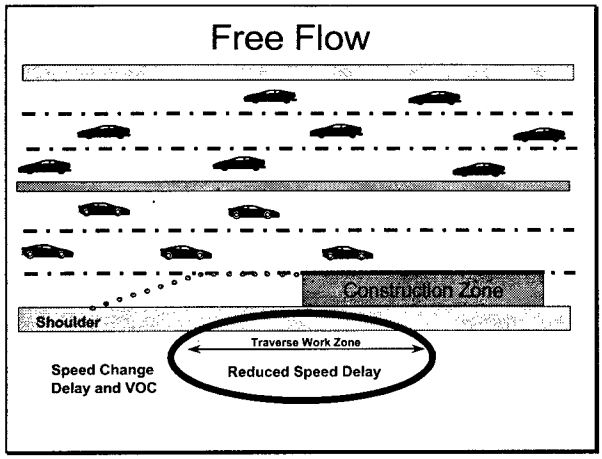
## 5. Compute Reduced Speed Delay

✓ Traverse Work Zone



✓ Que

29



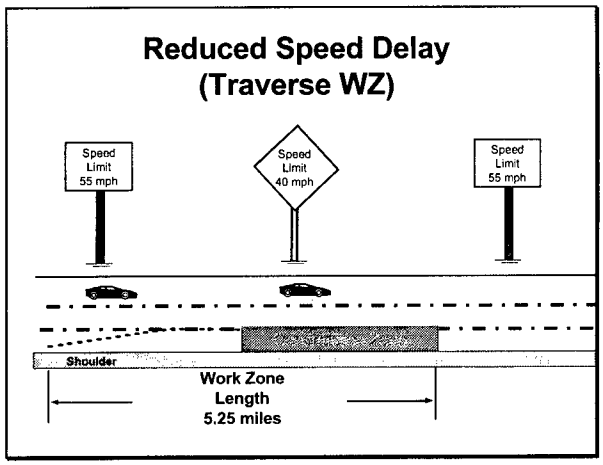

30

## Reduced Speed Delay (Traverse WZ)

- Reduced speed delay is ...

  increased travel time necessary to traverse the work zone at the posted speed compared to the up stream posted speed

31



32

## Reduced Speed Delay (WZ)

Reduced Speed Delay =

$$\frac{\text{WZ Length}}{\text{WZ Speed}} - \frac{\text{WZ Length}}{\text{Upstream Speed}}$$

33

## Reduced Speed Delay (WZ)

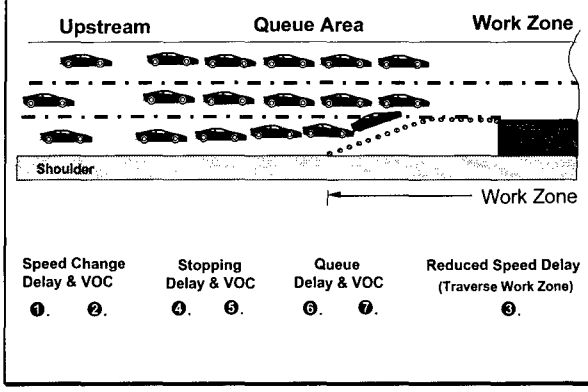
$$\frac{\text{WZ Length}}{\text{WZ Speed}} - \frac{\text{WZ Length}}{\text{Upstream Speed}}$$

$$\frac{5.25 \text{ Miles}}{40 \text{ mph}} - \frac{5.25 \text{ Miles}}{55 \text{ mph}}$$

➡ Delay / Vehicle = 0. 0358 Hours

34

Forced Flow



35

## Reduced Speed Delay (Queue)

Reduced Speed Delay =

$$\frac{\text{Queue Length}}{\text{Queue Speed}} - \frac{\text{Queue Length}}{\text{Upstream Speed}}$$

36

## Reduced Speed Delay (Queue)

Reduced Speed Delay =

$$\frac{\textbf{Queue Length}}{\textbf{Queue Speed}} - \frac{\textbf{Queue Length}}{\textbf{Upstream Speed}}$$

$$\frac{\text{? Miles}}{\text{? Mph}} - \frac{\text{? Miles}}{\text{55 mph}}$$

37

## Reduced Speed Delay (Queue)

- Determine queue speed
- Determine average queue length

38

## Reduced Speed Delay (Queue)

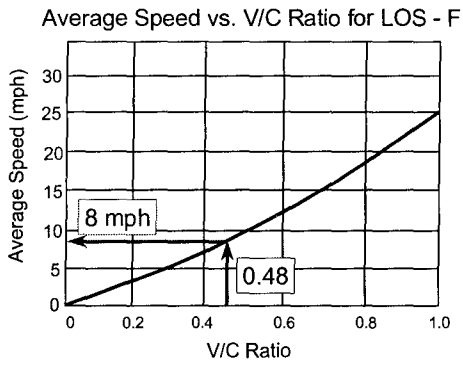
- Determine queue speed

$V/C = Vol_{Queue}/Capacity$

WZ Capacity  Upstream

$V/C = 3,027/6,285 = 0.48$

39




Source: NCHRP 133 (1972)

40

## Reduced Speed Delay

### Queue

$$\frac{\text{Queue Length}}{\text{Queue Speed}} - \frac{\text{Queue Length}}{\text{Upstream Speed}}$$

$$\frac{\text{? Miles}}{\text{8 Mph}} - \frac{\text{? Miles}}{\text{55 mph}}$$

41

## Reduced Speed Delay (Queue)

- ✓ Determine queue speed
- ■ Determine average queue length

42

## Reduced Speed Delay (Queue)

Average Queue Length =

Maximum Queue Length / 2

43

Twenty Four Hour Analysis Period - SouthBound

| Hour | Hourly Distr. (%) | Demand (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ @40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e+f_{i-1})$ | IF f > 0,c,0 | See Note** | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 0 - 1 | 0.9 | 607 | 3,027 | (2,420) | 0 | 0 | 607 | 607 |
| 1 - 2 | 0.5 | 337 | 3,027 | (2,690) | 0 | 0 | 337 | 337 |
| 2 - 3 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 3 - 4 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 4 - 5 | 0.6 | 404 | 3,027 | (2,623) | 0 | 0 | 404 | 404 |
| 5 - 6 | 1.8 | 1,213 | 6,285 | (5,072) | 0 | 0 | 0 | 0 |
| 6 - 7 | 4.4 | 2,966 | 6,285 | (3,319) | 0 | 0 | 0 | 0 |
| 7 - 8 | 6.2 | 4,179 | 6,285 | (2,106) | 0 | 0 | 0 | 0 |
| 8 - 9 | 5.7 | 3,842 | 6,285 | (2,443) | 0 | 0 | 0 | 0 |
| 9 - 10 | 5.1 | 3,438 | 3,027 | 411 | 411 | 3,438 | 3,027 | 0 |
| 10 - 11 | 5.2 | 3,505 | 3,027 | 478 | 889 | 3,505 | 3,027 | 0 |
| 11 - 12 | 5.6 | 3,775 | 3,027 | 748 | 1,637 | 3,775 | 3,027 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

** If(d=3027,If (c>d,d,c),0)

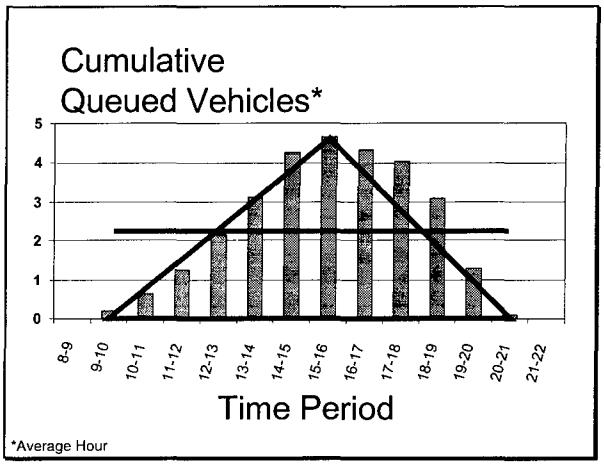
**44**

Table Continued

| Hour | Hourly Distr. (%) | Demand (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ at 40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e_i+f_{i-1})$ | IF f > 0,c,0 | See Note** | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 12 - 13 | 6.0 | 4,044 | 3,027 | 1,017 | 2,654 | 4,044 | 3,027 | 0 |
| 13 - 14 | 5.9 | 3,977 | 3,027 | 950 | 3,604 | 3,977 | 3,027 | 0 |
| 14 - 15 | 6.4 | 4,314 | 3,027 | 1,287 | 4,891 | 4,314 | 3,027 | 0 |
| 15 - 16 | 7.4 | 4,988 | 5,454 | (466) | 4,425 | 4,988 | 0 | 0 |
| 16 - 17 | 7.8 | 5,258 | 5,454 | (196) | 4,229 | 5,258 | 0 | 0 |
| 17 - 18 | 7.5 | 5,055 | 5,454 | (399) | 3,830 | 5,055 | 0 | 0 |
| 18 - 19 | 5.9 | 3,977 | 5,454 | (1,477) | 2,353 | 3,977 | 0 | 0 |
| 19 - 20 | 4.9 | 3,303 | 5,454 | (2,151) | 202 | 3,303 | 0 | 0 |
| 20 - 21 | 4.0 | 2,696 | 3,027 | (331) | 0 | **1,646** * | 2,898 | 1,051 |
| 21 - 22 | 3.3 | 2,224 | 3,027 | (803) | 0 | 0 | 2,224 | 2,224 |
| 22 - 23 | 2.4 | 1,618 | 3,027 | (1,409) | 0 | 0 | 1,618 | 1,618 |
| 23 - 24 | 1.7 | 1,146 | 3,027 | (,1881) | 0 | 0 | 1,146 | 1,146 |
| | | | | Total | | **47,279** | **27,936** | **7,926** |

*Prorated based on portion of hour required to clear queue. ** If(d=3027,If (c>d,d,c),0)

**45**




*Average Hour

**46**

## Reduced Speed Delay (Queue)

Caution:

- Queue could grow and stabilize for a period of time and then dissipate.
- This would support calculating queue length on a per hour basis.

47

## Reduced Speed Delay (Queue)

Average Queue Length =

Maximum Queue Length / 2

48

## Reduced Speed Delay (Queue)

Maximum Queue Length =

$$\frac{\text{Maximum No. of Queued Vehicles}}{\text{Change in Traffic Density}}$$

49

## Traffic Density (veh./mi.)

- The number of vehicles on a mile of road.
- Computed by ...
- Volume / Speed (vph/mph)

50

## Change in Traffic Density

WZ Capacity at max. no. queued veh. = Demand at max. no. queued veh.

$$\frac{\text{Queue Volume}}{\text{Queue Speed}} = \frac{\text{Upstream Volume}}{\text{Upstream Speed}}$$

51

## Change in Traffic Density

=

$$\frac{\text{Queue Volume}}{\text{Queue Speed}} - \frac{\text{Upstream Volume}}{\text{Upstream Speed}}$$

$$\frac{\text{? Vph}}{\text{8 mph}} - \frac{\text{? Vph}}{\text{55 mph}}$$

52

Twenty Four Hour Analysis Period - SouthBound

| Hour | Hourly Distr. (%) | Demand (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ @40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e_i+f_{i-1})$ | IF f > 0,c,0 | IF d=3027,c,0 | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 0 - 1 | 0.9 | 607 | 3,027 | (2,420) | 0 | 0 | 607 | 607 |
| 1 - 2 | 0.5 | 337 | 3,027 | (2,690) | 0 | 0 | 337 | 337 |
| 2 - 3 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 3 - 4 | 0.4 | 270 | 3,027 | (2,757) | 0 | 0 | 270 | 270 |
| 4 - 5 | 0.6 | 404 | 3,027 | (2,623) | 0 | 0 | 404 | 404 |
| 5 - 6 | 1.8 | 1,213 | 6,285 | (5,072) | 0 | 0 | 0 | 0 |
| 6 - 7 | 4.4 | 2,966 | 6,285 | (3,319) | 0 | 0 | 0 | 0 |
| 7 - 8 | 6.2 | 4,179 | 6,285 | (2,106) | 0 | 0 | 0 | 0 |
| 8 - 9 | 5.7 | 3,842 | 6,285 | (2,443) | 0 | 0 | 0 | 0 |
| 9 - 10 | 5.1 | 3,438 | 3,027 | 411 | 411 | 3,438 | 3,027 | 0 |
| 10 - 11 | 5.2 | 3,505 | 3,027 | 478 | 889 | 3,505 | 3,027 | 0 |
| 11 - 12 | 5.6 | 3,775 | 3,027 | 748 | 1,637 | 3,775 | 3,027 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

**53**

Table Continued

| Hour | Hourly Distr. (%) | Demand (vph) | Cap. (vph) | Queue Rate (vph) | Queued Veh. | Vehicles that ... Stop 55-0-55 | Traverse WZ at 40 mph | Slowdown 55-40-55 |
|---|---|---|---|---|---|---|---|---|
| | | (AADT)(b) | | (c-d) | $(e_{-1}+f_{-1})$ | IF f > 0,c,0 | IF d=3027,c,0 | IF g=0, h,0 |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
| 12 - 13 | 6.0 | 4,044 | 3,027 | 1,017 | 2,654 | 4,044 | 3,027 | 0 |
| 13 - 14 | 5.9 | 3,977 | 3,027 | 950 | 3,604 | 3,977 | 3,027 | 0 |
| 14 - 15 | 6.4 | 4,314 | 3,027 | 1,287 | 4,891 | 4,314 | 3,027 | 0 |
| 15 - 16 | 7.4 | 4,988 | 5,454 | (466) | 4,425 | 4,988 | 0 | 0 |
| 16 - 17 | 7.8 | 5,258 | 5,454 | (196) | 4,229 | 5,258 | 0 | 0 |
| 17 - 18 | 7.5 | 5,055 | 5,454 | (399) | 3,830 | 5,055 | 0 | 0 |
| 18 - 19 | 5.9 | 3,977 | 5,454 | (1,477) | 2,353 | 3,977 | 0 | 0 |
| 19 - 20 | 4.9 | 3,303 | 5,454 | (2,151) | 202 | 3,303 | 0 | 0 |
| 20 - 21 | 4.0 | 2,696 | 3,027 | (331) | 0 | **1,646** * | 2,898 | 1,051 |
| 21 - 22 | 3.3 | 2,224 | 3,027 | (803) | 0 | 0 | 2,224 | 2,224 |
| 22 - 23 | 2.4 | 1,618 | 3,027 | (1,409) | 0 | 0 | 1,618 | 1,618 |
| 23 - 24 | 1.7 | 1,146 | 3,027 | (,1881) | 0 | 0 | 1,146 | 1,146 |
| | | | | Total | | **47,279** | **27,936** | **7,926** |

*Prorated based on portion of hour required to clear queue.

**54**

## Change in Traffic Density

=

$$\frac{\text{Queue Volume}}{\text{Queue Speed}} - \frac{\text{Upstream Volume}}{\text{Upstream Speed}}$$

$$\frac{(3027 \text{ vph})}{(8 \text{ mph})} - \frac{(4314 \text{ vph})}{(55 \text{ mph})}$$

**55**

## Change in Traffic Density

=

$$\frac{\text{Queue Volume}}{\text{Queue Speed}} - \frac{\text{Upstream Volume}}{\text{Upstream Speed}}$$

$$\frac{(3027 \text{ vph})}{(8 \text{ mph})} - \frac{(4314 \text{ vph})}{(55 \text{ mph})}$$

= 300 veh./mi.

56

## Reduced Speed Delay (Queue)

Maximum Queue Length =

$$\frac{\text{Maximum no. of Queued Vehicles}}{\text{Change in traffic density}}$$

$$\frac{4{,}891 \text{ vehicles}}{300 \text{ vehicles/mile}} = 16.3 \text{ Miles}$$

57

## Reduced Speed Delay (Queue)

Average Queue Length =

Maximum Queue Length / 2

$$= \frac{16.3 \text{ Miles}}{2} = 8.15 \text{ Miles}$$

58

## Reduced Speed Delay

### Queue

$$\frac{\text{Queue Length}}{\text{Queue Speed}} - \frac{\text{Queue Length}}{\text{Upstream Speed}}$$

$$\frac{8.15 \text{ Miles}}{8 \text{ Mph}} - \frac{8.15 \text{ Miles}}{55 \text{ mph}}$$

59

## Reduced Speed Delay

### Queue

Queue Length / Queue Speed − Queue Length / Upstream Speed

8.15 Miles / 8 Mph − 8.15 Miles / 55 mph

1.02 Hours − 0.15 Hours

➡ Delay / Vehicle = 0. 87 Hours

60

## 6. Assign VOC Cost Rates

Sources:

- NCHRP 133 Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects, 1972
- Economic Analysis for Highways, Winfrey 1969

61

Added Time & Veh. Running Cost / 1000 Stops and Idling Costs (Aug. 1996 values)

| Initial Speed (mph) | Added Time (Hr/1000 Stops) (Excludes Idling Time) | | | Added Cost ($/1000 Stops) (Excludes Idling Cost) | | |
|---|---|---|---|---|---|---|
| | Pass Cars | Single Unit Trk | Comb. Truck | Pass Cars | Single Unit Trk | Comb. Truck |
| 5 | 1.02 | 0.73 | 1.10 | 2.70 | 9.25 | 33.62 |
| 10 | 1.51 | 1.47 | 2.27 | 8.83 | 20.72 | 77.49 |
| 15 | 2.00 | 2.20 | 3.48 | 15.16 | 33.89 | 129.97 |
| 20 | 2.49 | 2.93 | 4.76 | 21.74 | 48.40 | 190.06 |
| 25 | 2.98 | 3.67 | 6.10 | 28.67 | 63.97 | 256.54 |
| 30 | 3.46 | 4.40 | 7.56 | 36.10 | 80.23 | 328.21 |
| 35 | 3.94 | 5.13 | 9.19 | 44.06 | 96.88 | 403.84 |
| 40 | 4.42 | 5.87 | 11.09 | 52.70 | 113.97 | 482.21 |
| 45 | 4.90 | 6.60 | 13.39 | 62.07 | 130.08 | 562.14 |
| 50 | 5.37 | 7.33 | 16.37 | 72.31 | 145.96 | 642.41 |
| 55 | 5.84 | 8.07 | 20.72 | 83.47 | 160.89 | 721.77 |
| 60 | 6.31 | 8.80 | 27.94 | 95.70 | 178.98 | 798.99 |
| 65 | 6.78 | 9.53 | NA | 109.02 | 195.84 | NA |
| 70 | 7.25 | NA | NA | 123.61 | NA | NA |
| 75 | 7.71 | NA | NA | 139.53 | NA | NA |
| 80 | 8.17 | NA | NA | 156.85 | NA | NA |
| Idling Cost ($ / Veh-Hr.) | | | | 0.6927 | 0.7681 | 0.8248 |

62

Example

55 mph → 40 mph → 55 mph

| Initial Speed (mph) | Added Time (Hr/1000 Stops) (Excludes Idling Time) Pass Cars | Single Unit Trk | Comb. Truck | Added Cost ($/1000 Stops) (Excludes Idling Cost) Pass Cars | Single Unit Trk | Comb. Truck |
|---|---|---|---|---|---|---|
| 5 | 1.02 | 0.73 | 1.10 | 2.70 | 9.25 | 33.62 |
| 10 | 1.51 | 1.47 | 2.27 | 8.83 | 20.72 | 77.49 |
| 15 | 2.00 | 2.20 | 3.48 | 15.16 | 33.89 | 129.97 |
| 20 | 2.49 | 2.93 | 4.76 | 21.74 | 48.40 | 190.06 |
| 25 | 2.98 | 3.67 | 6.10 | 28.67 | 63.97 | 256.54 |
| 30 | 3.46 | 4.40 | 7.56 | 36.10 | 80.23 | 328.21 |
| 35 | 3.94 | 5.13 | 9.19 | 44.06 | 96.88 | 403.84 |
| 40 | 4.42 | 5.87 | 11.09 | 52.70 | 113.97 | 482.21 |
| 45 | 4.90 | 6.60 | 13.39 | 62.07 | 130.08 | 562.14 |
| 50 | 5.37 | 7.33 | 16.37 | 72.31 | 145.96 | 642.41 |
| 55 | 5.84 | 8.07 | 20.72 | 83.47 | 160.89 | 721.77 |
| 60 | 6.31 | 8.80 | 27.94 | 95.70 | 178.98 | 798.99 |
| 65 | 6.78 | 9.53 | NA | 109.02 | 195.84 | NA |
| 70 | 7.25 | NA | NA | 123.61 | NA | NA |
| 75 | 7.71 | NA | NA | 139.53 | NA | NA |
| 80 | 8.17 | NA | NA | 156.85 | NA | NA |
| Idling Cost ($ / Veh-Hr.) | | | | 0.6927 | 0.7681 | 0.8248 |

63

Example

Added Time & Veh. Running Cost / 1000 Stops and Idling Costs (Aug. 1996 values)

| Initial Speed (mph) | Added Time (Hr/1000 Stops) (Excludes Idling Time) Pass Cars | Single Unit Trk | Comb. Truck | Added Cost ($/1000 Stops) (Excludes Idling Cost) Pass Cars | Single Unit Trk | Comb. Truck |
|---|---|---|---|---|---|---|
| 55 | 5.84 | 8.07 | 20.72 | 83.47 | 160.89 | 721.77 |
| 40 | 4.42 | 5.87 | 11.09 | 52.70 | 113.97 | 482.21 |
| 55-40-55 | 1.42 | 2.20 | 9.63 | 30.77 | 46.92 | 239.56 |

64

## Note:

Update tables to current year

- Value of time
  - Overall current CPI to base year overall CPI
- VOC
  - Current year transportation component CPI to base year transportation component

65

## 7. Assign Delay Cost Rates

### Value of Time

| Vehicle Class | $ / Vehicle Hour | |
|---|---|---|
| | Value | Range |
| Passenger Vehicles | 11.58 | 10 - 13 |
| Single Unit Trucks | 18.54 | 17 - 19 |
| Combination Trucks | 22.31 | 21 - 24 |

Aug. 1996 Dollars

66

## 8. Assign Traffic to Vehicle Classes

Vehicle classification:

- Passenger vehicles
  - Personal
  - Commercial
- Single unit trucks
- Combination trucks

67

| | | Cost Component | Vehicle Class | No. Vehicles |
|---|---|---|---|---|
| Free Flow | ❶ | WZ Speed Change Delay | Pass | 428,012 |
| | | (55-40-55) | SU | 25,681 |
| | | (475,569)(%Class)= | Comb | 21,786 |
| | ❷ | WZ Speed Change VOC | Pass | 428,012 |
| | | (55-40-55) | SU | 25,681 |
| | | (475,569)(%Class)= | Comb | 21,786 |
| | ❸ | WZ Reduced Speed Delay | Pass | 1,508,537 |
| | | (Traverse WZ at 40 mph) | SU | 90,512 |
| | | (1,676,152)(%Class)= | Comb | 77,103 |
| Forced Flow | ❹ | Queue Stopping Delay | Pass | 2,553,086 |
| | | (55-0-55) | SU | 153,185 |
| | | (2,836,762)(%Class)= | Comb | 130,491 |
| | ❺ | Queue Stopping VOC | Pass | 2,553,086 |
| | | (55-0-55) | SU | 153,185 |
| | | (2,836,762)(%Class)= | Comb | 130,491 |
| | ❻ | Queue Added Travel Delay | Pass | 2,553,086 |
| | | (Traverse Queue at 8 mph) | SU | 153,185 |
| | | (2,836,762)(%Class) | Comb | 130,491 |
| | ❼ | Queue Idle VOC | Pass | 2,553,086 |
| | | | SU | 153,185 |
| | | (2,836,762)(%Class) | Comb | 130,491 |

68

## 9. Compute User Costs by Vehicle Class

69

| Cost Component | Vehicle Class | No. Vehicles | Added Time (hpv) | Cost Factor | Cost ($) | %of Total |
|---|---|---|---|---|---|---|
| ❶WZ Speed Change Delay 55 ➡.40 ➡.55 mph | Pass | 428,012 | 0.00142 | 11.58 | 7,038 | 0.02 |
| | SU | 25,681 | 0.00220 | 18.54 | 1,047 | 0.00 |
| | Comb | 21,876 | 0.00963 | 22.31 | 4,700 | 0.01 |
| ❷WZ Speed Change VOC 55 ➡.40 ➡.55 mph | Pass | 428,012 | | 0.03077 | 13,170 | 0.04 |
| | SU | 25,681 | | 0.04692 | 1,205 | 0.00 |
| | Comb | 21,876 | | 0.23956 | 5,241 | 0.02 |
| ❸WZ Reduced Speed Delay 40 vs 55 mph | Pass | 1,508,537 | 0.0358 | 11.58 | 625,385 | 1.85 |
| | SU | 90,512 | 0.0358 | 18.54 | 60,076 | 0.18 |
| | Comb | 77,103 | 0.0358 | 22.31 | 61,582 | 0.18 |
| ❹Queue Stopping Delay 55 ➡.0 ➡.55 mph | Pass | 2,553,086 | 0.00584 | 11.58 | 172,658 | 0.51 |
| | SU | 153,185 | 0.00807 | 18.54 | 22,919 | 0.07 |
| | Comb | 130,491 | 0.02072 | 22.31 | 60,321 | 0.18 |
| ❺Queue Stopping VOC 55 ➡.0 ➡.55 mph | Pass | 2,553,086 | | 0.08347 | 213,106 | 0.63 |
| | SU | 153,185 | | 0.16089 | 24,646 | 0.07 |
| | Comb | 130,491 | | 0.72177 | 94,185 | 0.28 |
| ❻Queue Added Travel Delay [illegible] | Pass | 2,553,086 | 0.87 | [illegible] | [illegible] | 6.04 |
| | SU | 153,185 | 0.87 | [illegible] | [illegible] | 7.30 |
| | Comb | 130,491 | 0.87 | [illegible] | [illegible] | 7.49 |
| ❼Queue Idle VOC | Pass | 2,553,086 | 0.87 | 0.6927 | 1,538,615 | 4.55 |
| | SU | 153,185 | 0.87 | 0.7681 | 102,366 | 0.30 |
| | Comb | 130,491 | 0.87 | 0.8248 | 93,637 | 0.28 |

**Total WZ User Cost = $33,826,855**

70

## Queue Added Travel Time Delay 8 vs 55 mph

| Vehicle Class | No. Vehicles | Added Time (hpv) | Cost Factor | Cost | % of Total |
|---|---|---|---|---|---|
| Pass | 2,553,086 | 0.87 | 11.58 | 25,721,320 | 76.04 |
| SU | 153,185 | 0.87 | 18.54 | 2,470,846 | 7.30 |
| Combo | 130,491 | 0.87 | 22.31 | 2,532,792 | 7.49 |

71

## 10. Determine Circuity

- Detours - 31cents per mile
  - Road closures
  - Self-imposed diversions
- Driver type

72

## Driver Types

- Hang Toughers
- Time Shifters
- Detourees
- Trip Swappers
- Trip Avoiders

73

## 11. Compute Crash Cost

Crash Cost = (Crash Rate) (Exposure) (Crash Cost)
[units] [crash/100 M VMT] [VMT] [$/crash]

Crash rate: Studies, MicroBENCOST
Exposure: Traffic data
Crash cost: MicroBENCOST defaults, Insurance, SHA

Note:
Crash rate and cost is determined by type of crash.

74

## Crash Costs

- Commonly assumed that Crashes triple in work zone compared to normal operation of facility
- Not much statistical data to support rule
- WZ Crash rates?

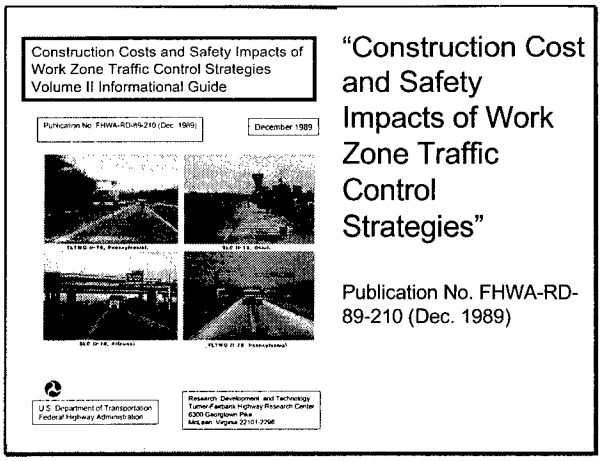
75

## Crash Injury Rates Computed From *1995 Highway Statistics*

Persons Injured per 100 Million VMT

| | Rural | | Urban | |
|---|---|---|---|---|
| Functional Class | Fatalities | Non-Fatal Injury | Fatalities | Non-Fatal Injury |
| Interstate | 1.0 | 25.0 | 0.6 | 74.3 |
| Other Freeways | - | - | 0.9 | 57.2 |
| Other Principal Arter | 2.1 | 55.8 | 1.6 | 208.8 |
| Minor Arterial | 2.8 | 108.6 | 1.3 | 175.8 |
| Major Collector | 2.7 | 100.8 | - | - |
| Minor Collector | 3.1 | 120.4 | - | - |
| Collectors | - | - | 2.0 | 172.4 |
| Local | 3.7 | 224.8 | 2.2 | 292.1 |

76




"Construction Cost and Safety Impacts of Work Zone Traffic Control Strategies"

Publication No. FHWA-RD-89-210 (Dec. 1989)

77

## Constraints of Study

- Single lane closure (SLC) versus two-lane two-way operation (TLTWO) Rural, 4-lane divided highways
- ADT: 10,000 to 30,000
- 51 projects in 11 states
- 3 had traffic delays

78

## Primary Findings

- Many variables influence WZ cost control strategy
- No statistical difference in Crash rates for SLC vs. TLTWO
- Fatal + injury Crashes had a signif. increase for both SLC and TLTWO
- No significant accidents to construction workers

79

## Annual Crashes / mi / 10k ADT

Single Lane Closure

| | Before | During | Change |
|---|---|---|---|
| Average | 2.256 | 3.414 | 1.159 |
| StdDev | 1.525 | 2.372 | |

Based on data from 26 projects.

Two Lane Two Way Oper.

| | Before | During | Change |
|---|---|---|---|
| Average | 3.241 | 3.057 | -0.184 |
| StdDev | 2.191 | 1.384 | |

Based on data from 22 projects.

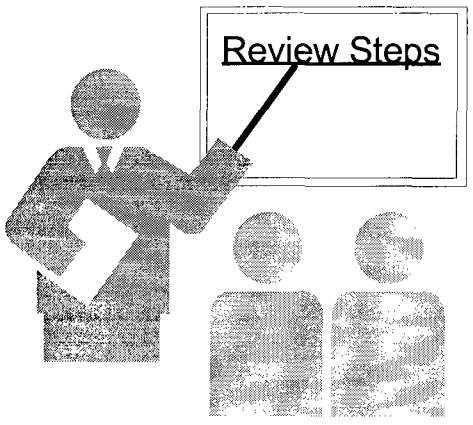
80

## 12. Sum Total Work Zone User Costs

Delay & VOC
+ Circuity
+ Crash

Total User Costs

81



82

## WZ User Costs Steps

1. Determine Capacity
2. Calculate Directional Hourly Demand
3. Identify User Cost Components
4. Quantify Traffic Affected by Each Component
5. Compute Reduced Speed Delay Times
6. Assign VOC Cost Rates

83

## WZ User Costs Steps (Con't)

7. Assign Delay Cost Rates
8. Assign Traffic to Vehicle Classes
9. Compute User Costs by Vehicle Class
10. Circuity
11. Crash Costs
12. Sum Total User Costs

84

## End Session

1

# Basic Statistics

2

## Session Overview

- Probability Concepts
- Probability Distributions
- Measures of Central Tendency
- Measures of Variability
- Interpreting Results

3

## Probability Concepts

- Probability is the likelihood of an event occurring
- Probabilities sum to 100%

4

## Two Same Birthdays

$$P = 1 - \left[\frac{365!}{(365-n)!\ (365^n)}\right]$$

n = number of people

23 people ... P = 51%

30 people ... P = 71%

5

## Probability Development

- Theoretical
  - Math
- Empirical
  - Experience

6

## Variables

- Discrete
- Continuous

7

## Discrete

- Countable
- Examples - rolling dice
  - birthday
  - # of accidents

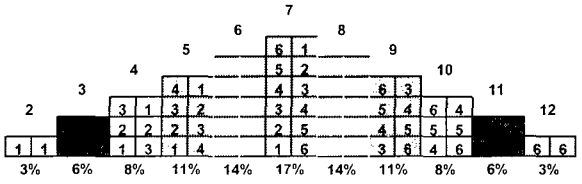
8

## DICE COMBINATIONS

| Dice | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |

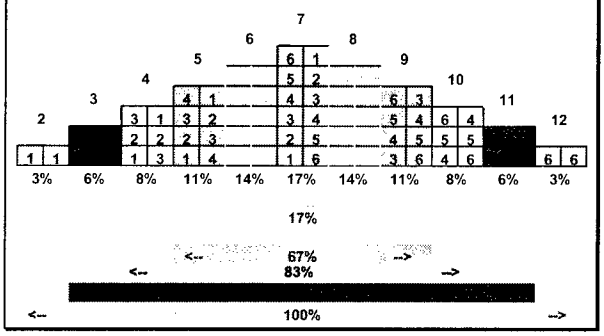
9

## Discrete Probability of Dice



10

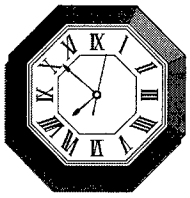
## Discrete Probability of Dice




11

## Continuous

- Uncountable



12

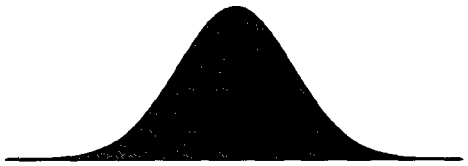
## Probability Distributions

- Common Varieties
  - Normal
  - Uniform
  - Triangular

13

## Normal Distribution

- Bell shaped curve
  - Intelligence tests
  - Defined by mean and std. dev.

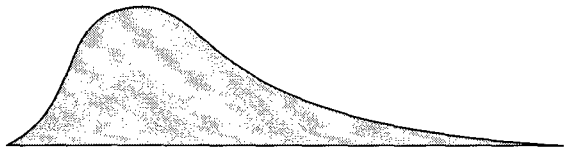


14

## Skewed Distribution

15

## Skewed Distribution



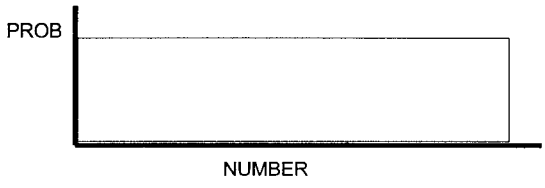
Salaries

Michael Jordan

16

## Uniform Distribution

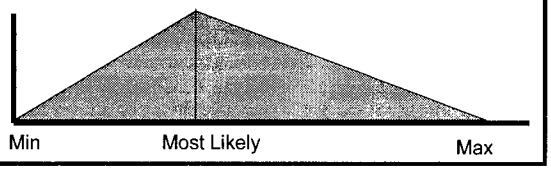
- Equal Chance
  - Lottery Numbers




17

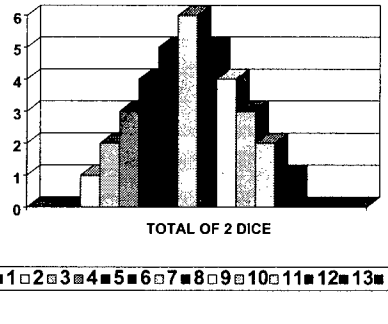
## Triangular Distribution

- Defined by:
  - Min - Most Likely - Max
- Handy for estimating



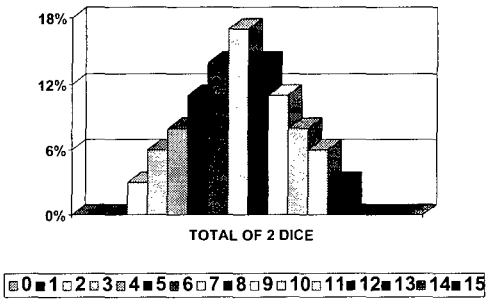

18

## Histogram



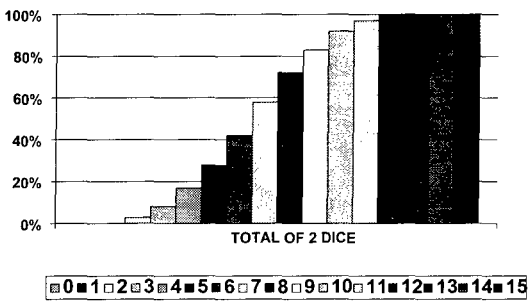
19

## Histogram with %



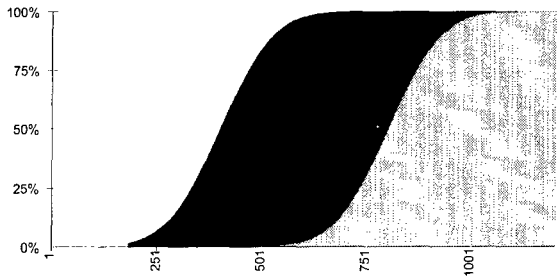

20

## Cumulative Ascending



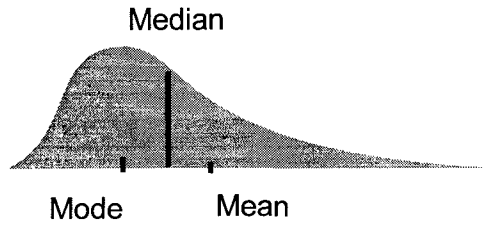

21

## Multiple Cumulative



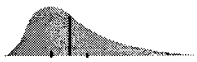
22

## Measures of Central Tendency




23

## Mode



- Point with the greatest frequency
- Used for quick estimate
- Identifies most common value
- More than one possible

24

## Median

- Equal number of variables on each side
- Not sensitive to extreme values

25

## Mean

- Balance point of distribution
- Sensitive to all scores
- Extreme values can effect

26

## Measures of Variability

- Range
- Standard Deviation
- Coefficient of Variation

27

## Range

- Difference between largest and smallest measurement in a set
- In our dice example the range should be 12 - 2 = 10

28

## Standard Deviation

- Root Mean Square of individual deviations from the mean
- Sensitive to all values

29

## Formula

- Population

$$\sigma = \sqrt{\sum (x_i - \bar{x})^2 / n}$$

- Sample

$$s = \sqrt{\sum (x_i - \bar{x})^2 / (n-1)}$$

30

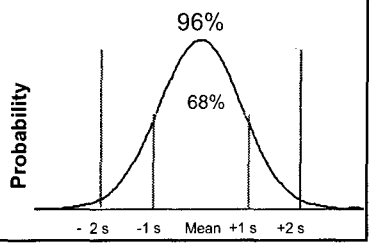
## Rule of Thumb

- Standard Deviation may be estimated by dividing the range by 4 to 6

31

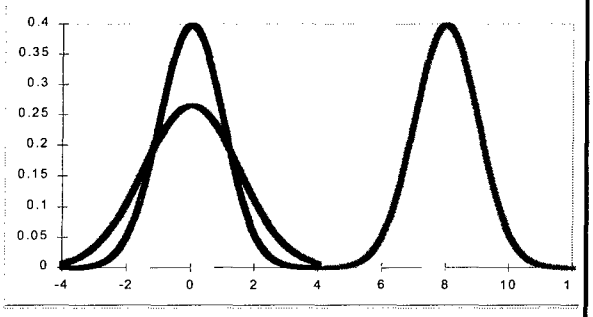
## Applications

- 68% of data within ± 1 σ
- 96% within ± 2 σ




32

## Means & Standard Deviations




33

## Coefficient of Variation

- COV = Std. Dev./ Mean
  - Mean = 120
  - Std. Dev. = 30
  - COV = 25%
- Use To Normalize Variation

34

Population - Set of all measurements of interest

Sample - Subset of measurements selected from the population

35

## Random Sample

- Each part of the population has an equal chance of being included in the sample

36

## Confidence Intervals

- There is a 95% probability that the mean height of class members is between 63 and 73 inches

37

## Difference Between Means

- Significance levels
- Statistical versus practical significance

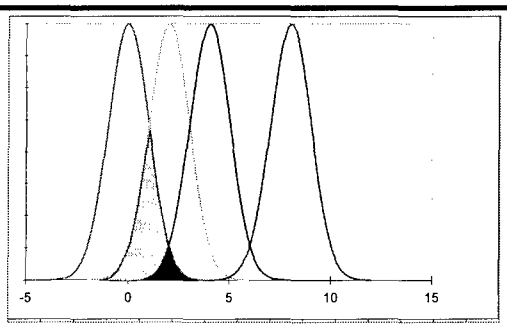
38

## Interpreting Results

- Percentiles
- Distributions
  - Overlapping
  - Cumulative

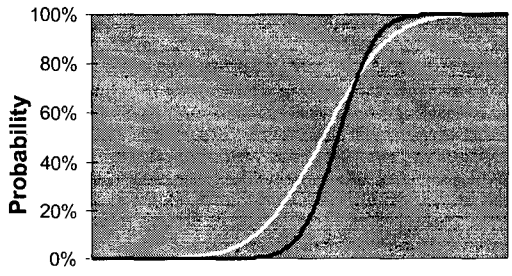
39

## Overlapping Normals



40

## Overlapping Cumulative




41

## Correlation

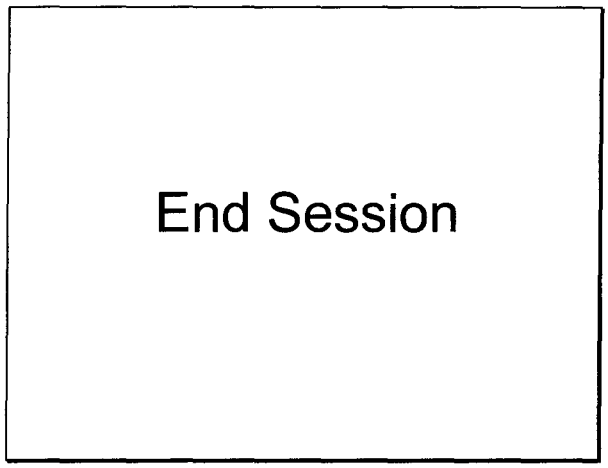
- How well does a regression equation describe the data
- $R^2 = 1.0$ Perfect
- $R^2 = 0.0$ None
- Percentage of variation described by equation

42

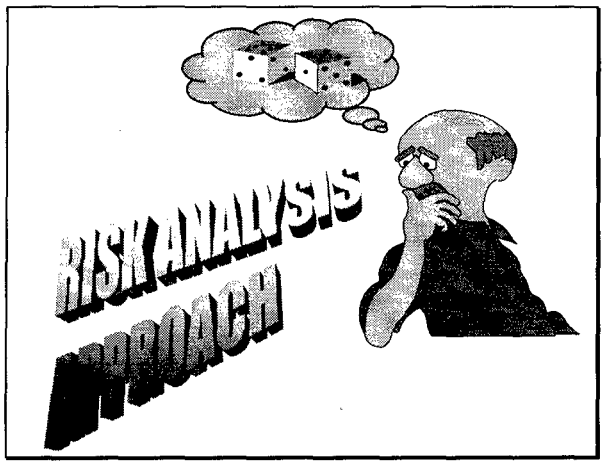
## Interpreting R

- R>0
  - Positive correlation
- R<0
  - Negative correlation

43



1




2

## Session Overview

- Deterministic Approach
- Sources of Variability
- Risk Analysis Approach
- Applications
- Advantages/Disadvantages

3

## Deterministic Approach

- Select discrete point values
  - Initial cost
  - Future cost
  - Timing of future cost
  - Value of time
  - Discount rate
- Compute discrete alternative NPV

4

## Deterministic Approach

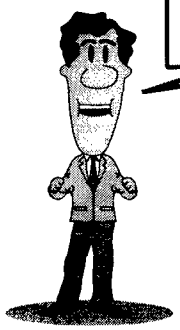
$ 29.4 M $ 26 M

NPV = Initial Cost +

Future Cost x $ 9 M $\left[\frac{1}{(1+i)^n}\right]$

5% 20 yrs

5



We didn't account for the variability of the inputs!

6

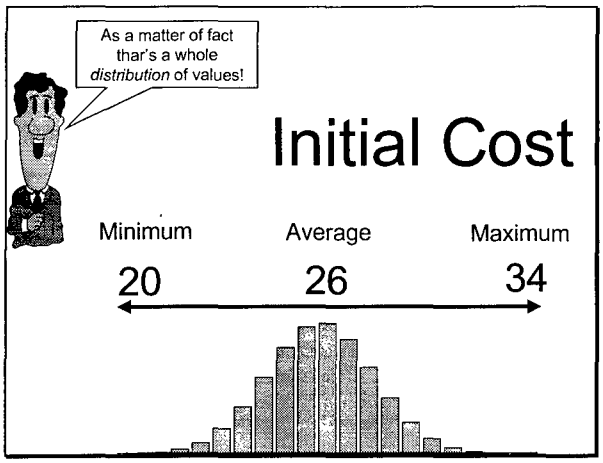
That's an entire range of possible values to use!

## Initial Cost

| Minimum | Average | Maximum |
|---|---|---|
| 20 | 26 | 34 |

Range

7




8

## Sources of Variability

Assumptions and estimates in ...

➡Agency Costs

- initial, rehab. construction, and maintenance activities --->materials, labor, overhead

➡User Costs

- Daily delay (traffic --> initial & growth rate, daily distribution), construction work days, value of time, ...

9

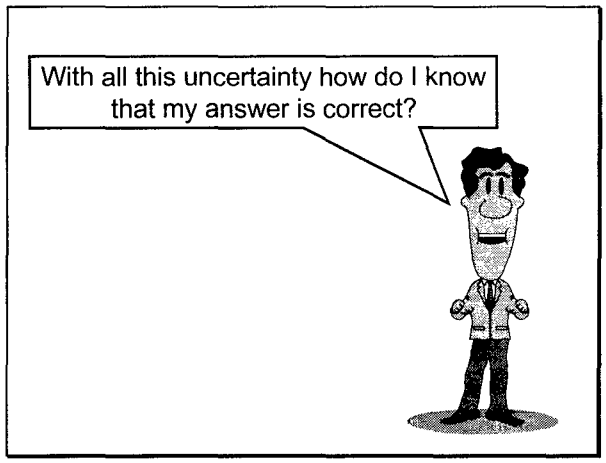
## Sources of Variability Con't

➡Discount Rate

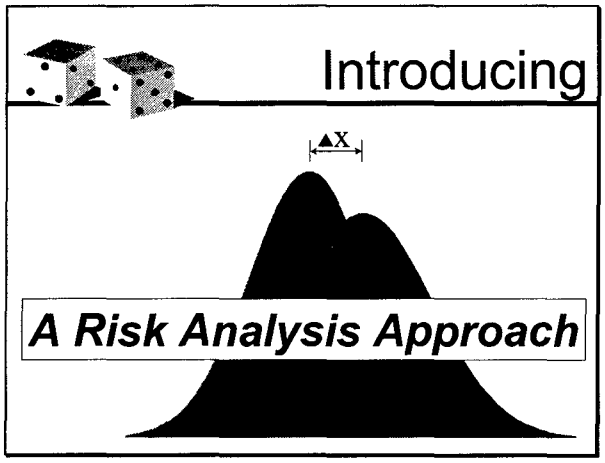
➡Performance

- Environment, traffic loading, subgrade properties, materials design and construction ...

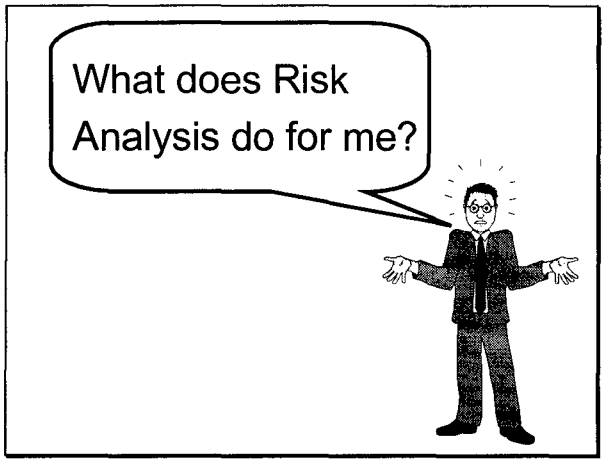
10


With all this uncertainty how do I know that my answer is correct?

11


Introducing
ΔX
A Risk Analysis Approach

12


What does Risk Analysis do for me?

13

## Risk Analysis ...

- Exposes areas of uncertainty
- Provides an opportunity to take mitigating action to reduce risk exposure
- Provides those vested with appropriate authority the opportunity to make decisions about risk taking

14

## What is Risk?

- Chance
- Uncertainty
- Deviation from the expected
- Possibility of loss or gain

15

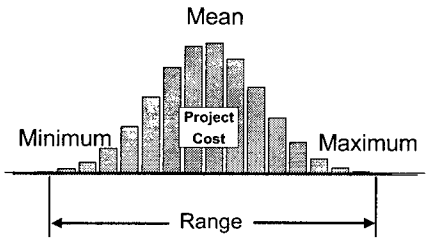
## Risk ...

- Subjective
  - Intuitively deciding how risky a situation is.
  - Example: Driving vs. Flying

- Objective
  - Quantitatively determining risks
  - 1996 Fatalities: 1070 Aviation 40676 Highways

16

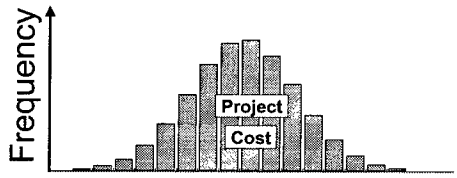
## Probability Distributions




❶ Range of Outcomes

17

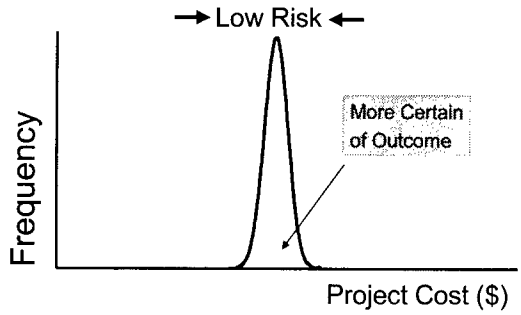
## Probability Distributions




❷ Likelihood of Occurrence

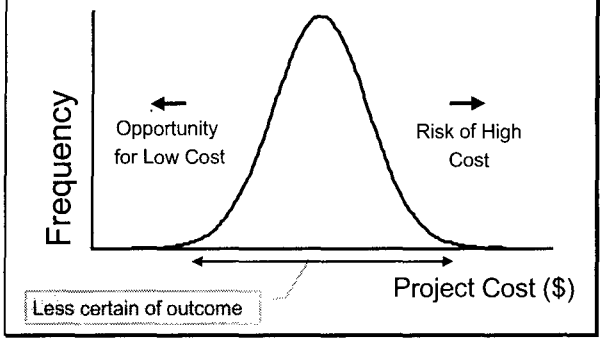
18

## Probability and Risk



19

## Probability and Risk




20

## Five Step Approach to Risk Analysis

1. Identify structure and logic of problem
2. Quantify assumptions w/ probabilistic descriptions of uncertain variables
3. Simulate problem to obtain results
4. Analyze and interpret results
5. Make consensus decision

21

## 1. Identify Structure and Logic of Problem

$$NPV = \text{Initial Cost} + \sum_{k=1}^{N} \text{Future Cost}_k \times \left[\frac{1}{(1+i)^{n_k}}\right]$$

i = discount rate
n = year of expenditure

22

## 2. Quantify Assumptions Using Probability

- Identify variables to include
- Describe uncertainty

23

## Variables to Include ...

- Agency costs
- User costs
- Timing of costs
- Discount rate

24

## Agency Costs

- Preliminary engineering
- Construction management
- Construction costs
- Maintenance costs

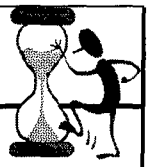
25

## User Costs

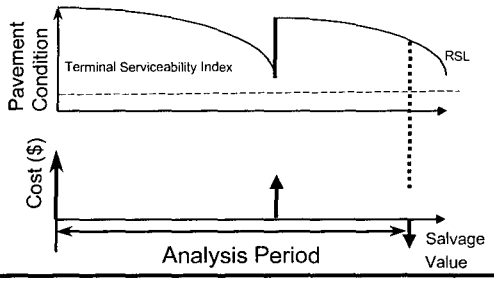
- Current traffic
- Future traffic
- Hourly demand
- Vehicle distributions
- Dollar value of delay time
- Work zone configuration
- Work zone hours of operation
- Work zone duration
- Work zone activity years
- Accident rates

26

## Timing of Costs



- Pavement performance




27

## Discount Rate

$$NPV = \text{Initial Cost} + \sum \text{Future Cost} \times \left[\frac{1}{(1+i)^n}\right]$$

28

## Describe Uncertainty

- Objective Method
- Subjective Method

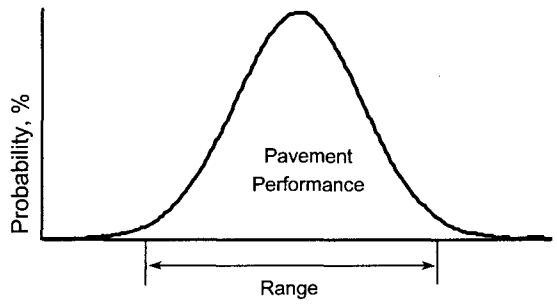
29

## Objective Method

- Historical data
  - BAMS
  - PMS
  - Research studies
  - Other
- Statistical analysis software
  - BestFit, ...

30

## Objective Method - Ideal



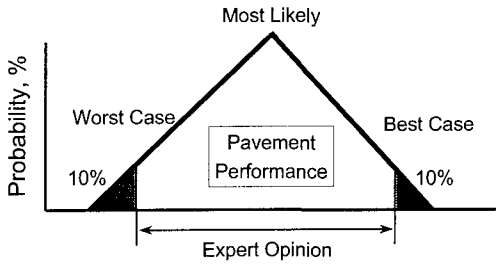
31

## Subjective Method

- Interviews
- Group discussion
  - Facilitated
  - Consensus Building
- Surveys

32

## Subjective Method




33

## 3. Simulate Problem to Obtain Results

Monte Carlo Simulation ...

- Values are randomly selected from input probability distributions
- Each randomly selected set is used to determine an outcome
- Combination of all outcomes form a probability distribution of results

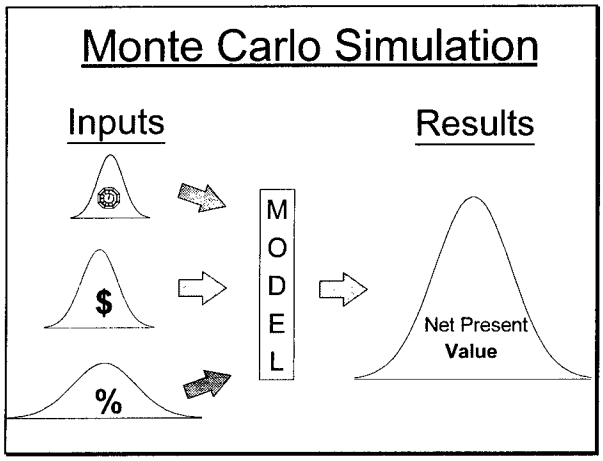
34

## Monte Carlo Simulation

- Rigorous extension of ...
  - best case
  - most likely
  - worst case
- Use empirical or theoretical equations
- Calculation intensive

35

## Monte Carlo Simulation



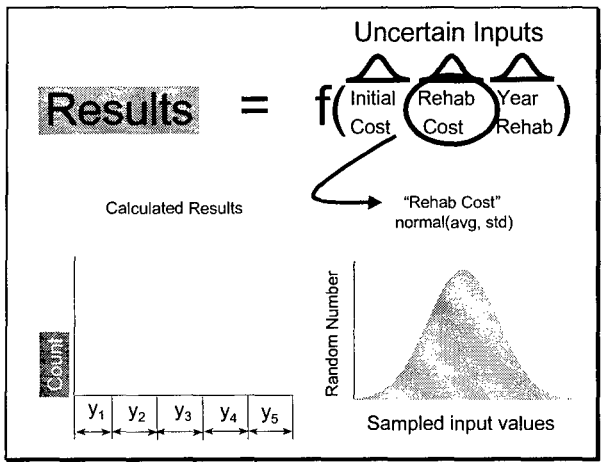

36

$$NPV = \text{Initial Cost} + \sum \text{Future Cost} \times \left[\frac{1}{(1+i)^n}\right]$$

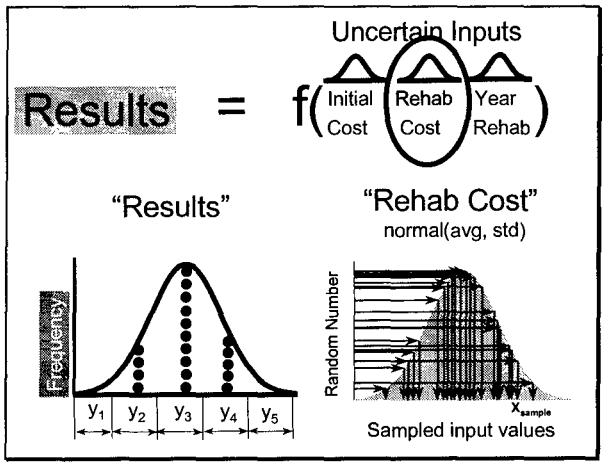
$$\text{Results} = f(\text{Initial Cost}, \text{Rehab Cost}, \text{Year Rehab})$$

Uncertain Inputs

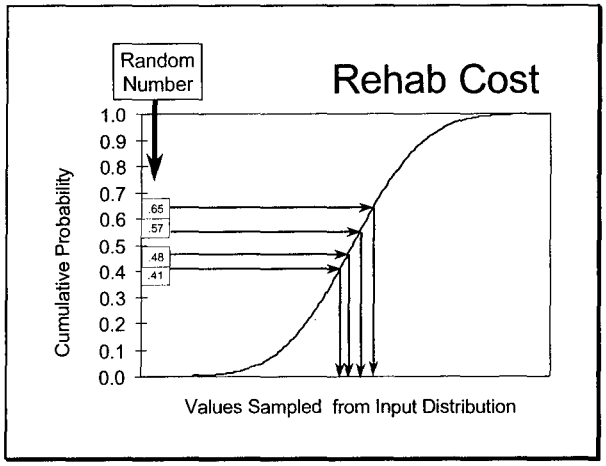
37


Uncertain Inputs
Results
=
f(
Initial Cost
Rehab Cost
Year Rehab
)
Calculated Results
"Rehab Cost"
normal(avg, std)
Count
$y_1$ $y_2$ $y_3$ $y_4$ $y_5$
Random Number
Sampled input values

38

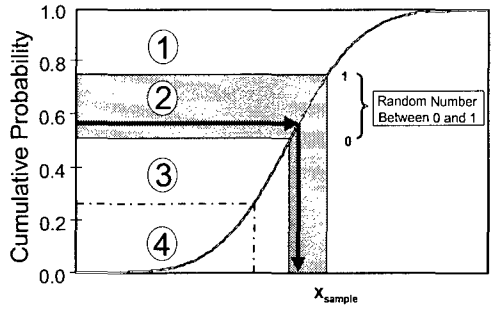

Uncertain Inputs
Results
=
f(
Initial Cost
Rehab Cost
Year Rehab
)
"Results"
"Rehab Cost"
normal(avg, std)
Frequency
$y_1$ $y_2$ $y_3$ $y_4$ $y_5$
Random Number
$x_{sample}$
Sampled input values

39


Random Number
Rehab Cost
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
.65
.57
.48
.41
Cumulative Probability
Values Sampled from Input Distribution

**40**

## Latin Hypercube




Values Sampled from Input Distribution

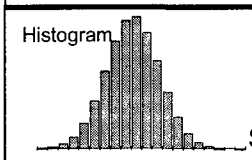
**41**

## Combine Variability of Inputs to Generate Probability Distribution of Results

$$NPV = \text{Initial Cost} + \sum \text{Future Cost} \times \left[\frac{1}{(1+i)^n}\right]$$

**42**

## 4. Analyze and Interpret Results




75th Percentile

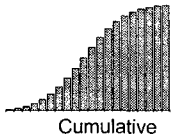
Standard Deviation

Minimum

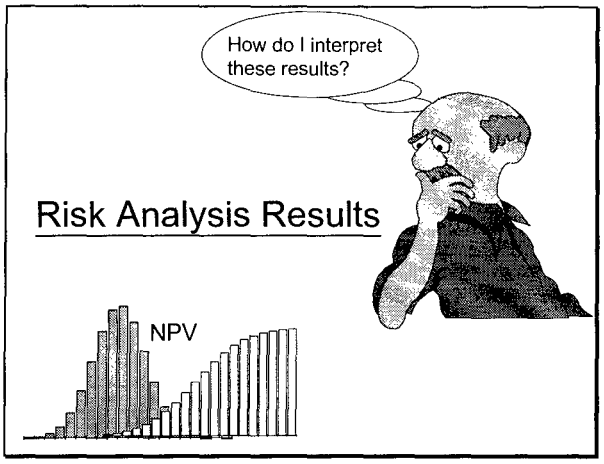
Mean

Maximum

90th Percentile



43



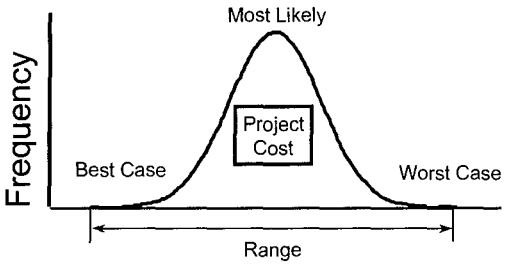

44

## Probabilistic results provide ...

❶ Distribution of "complete" range of outcomes

❷ Probability of occurrence

45

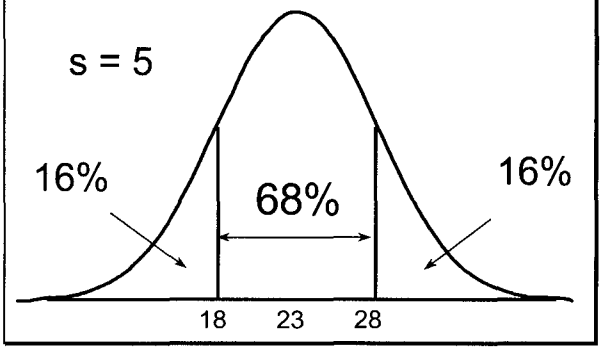



➡ Complete Range of Outcomes

➡ Likelihood of Occurrence

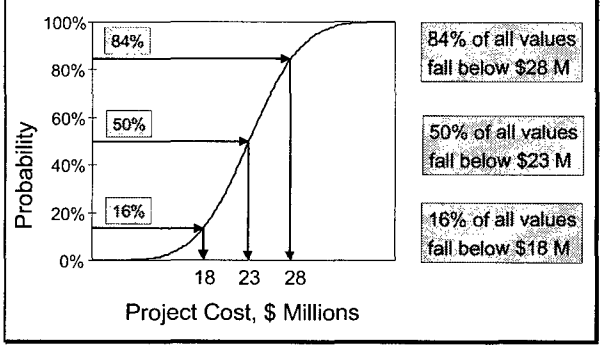
46

## Presenting Results: Histogram




47

## Presenting Results: Cumulative



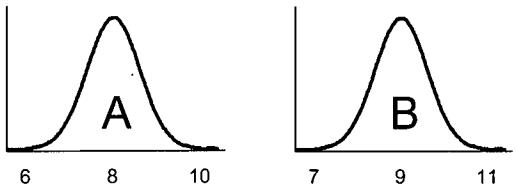

48

## Examples

49

## Agency NPV

$s_A = s_B$

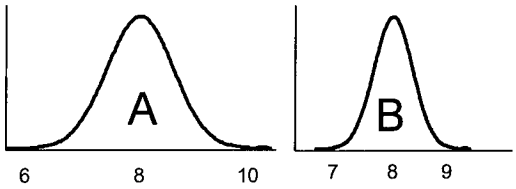



Which alternative do you select?

50

## Agency NPV

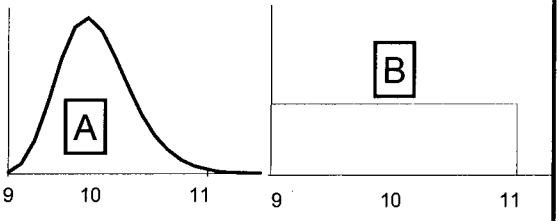
$s_B = 1/2\ s_A$




Which alternative do you select?

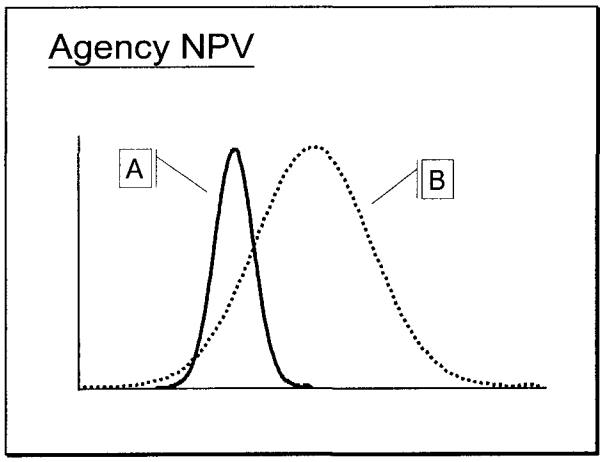
51

## Agency NPV

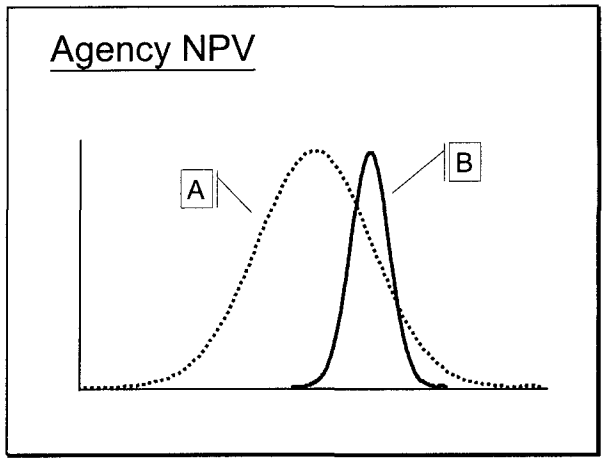



Which outcome has greater risk?

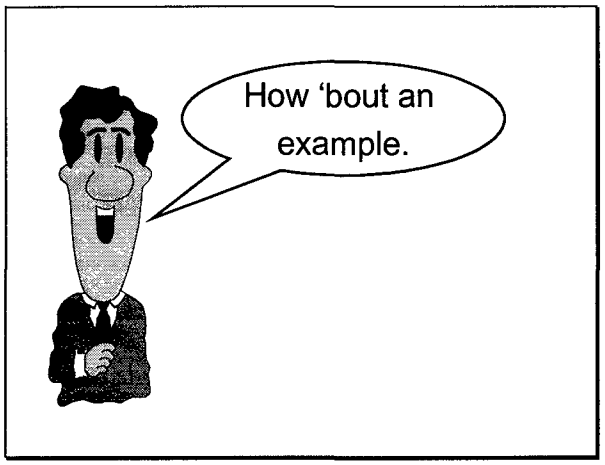
52



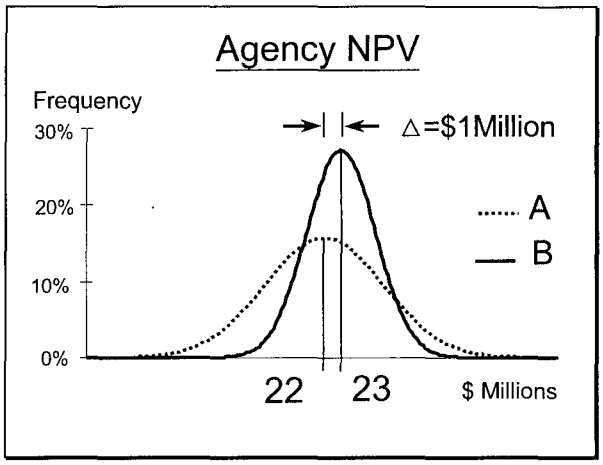

53



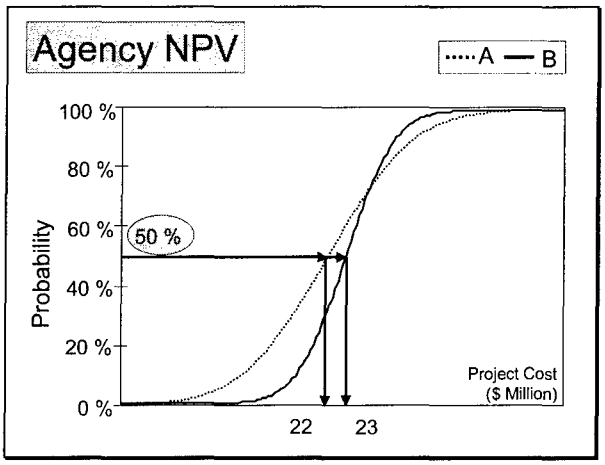

54



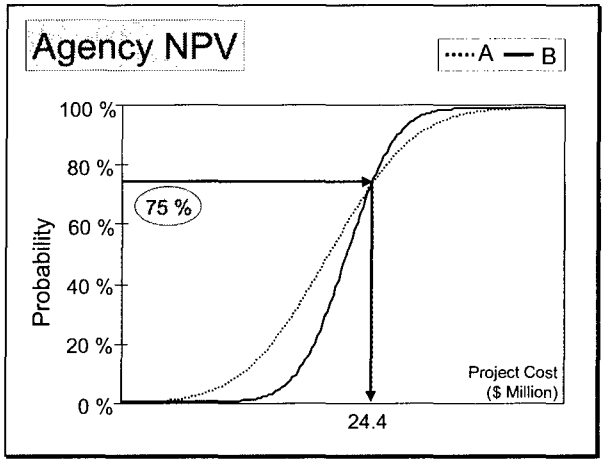
55


Agency NPV
Frequency
30%
20%
10%
0%
△=$1Million
..... A
— B
22
23
$ Millions

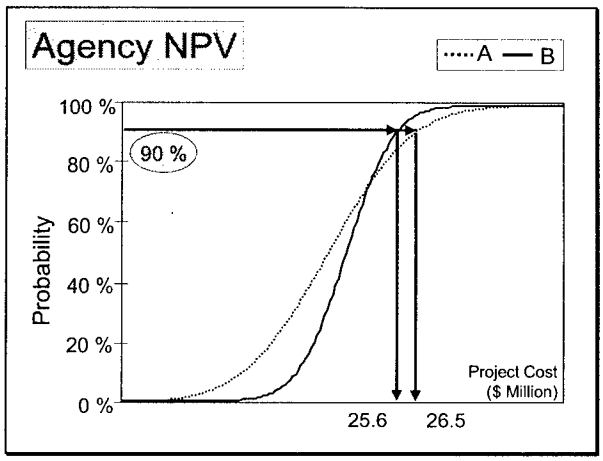
56


Agency NPV
.....A — B
100 %
80 %
60 %
40 %
20 %
0 %
Probability
50 %
Project Cost
($ Million)
22
23

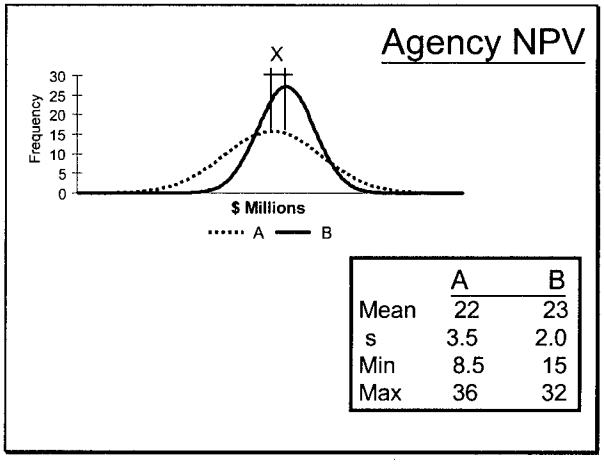
57


Agency NPV
.....A — B
100 %
80 %
60 %
40 %
20 %
0 %
Probability
75 %
Project Cost
($ Million)
24.4

**58**

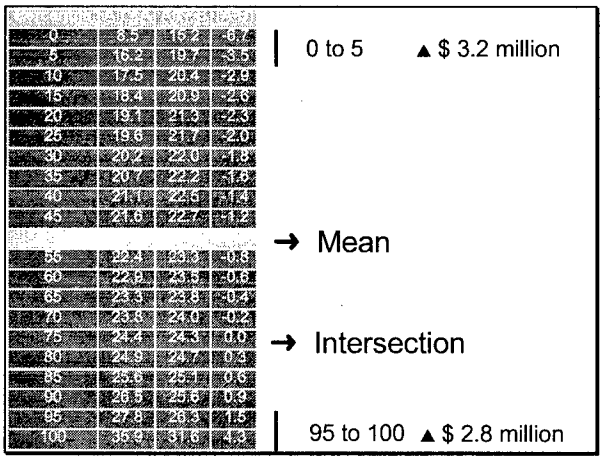



**59**




| | A | B |
|---|---|---|
| Mean | 22 | 23 |
| s | 3.5 | 2.0 |
| Min | 8.5 | 15 |
| Max | 36 | 32 |

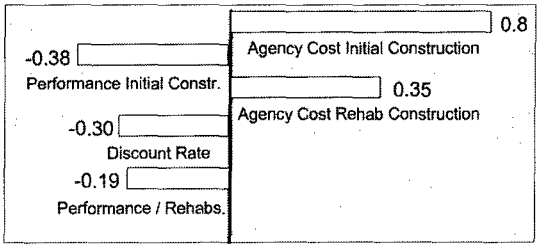
**60**



61

## Regression Sensitivity (Tornado Graphs)

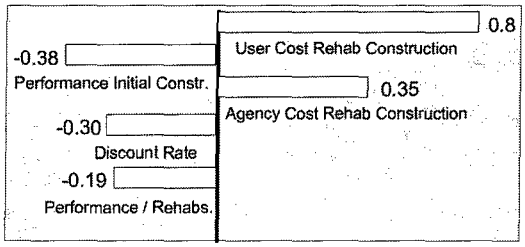
Agency Net Present Value




62

## Regression Sensitivity (Tornado Graphs)

Total Net Present Value




63

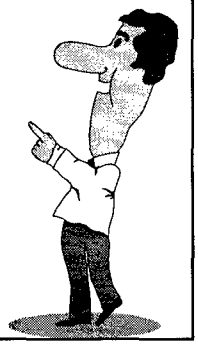
## Scenario Analysis

- Examine changes in policy variables
- Example:
  - Closing down a lane of traffic
    versus
  - Keeping traffic lane open
- Develop better alternatives

64

## 5. Make Consensus Decision

- Decisions about ...
  - Strategic Planning
  - Resource Allocation
  - Timing of Investments



65

## Risk Analysis Approach (Review)

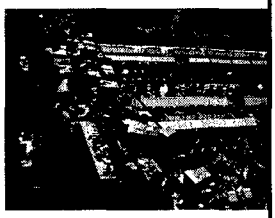
1. Identify structure and logic of problem
2. Quantify assumptions w/ probabilistic descriptions of uncertain variables
3. Simulate problem to obtain results
4. Analyze and interpret results
5. Make consensus decision

66

## Applications

- Investment & new product analysis

New Drug Research

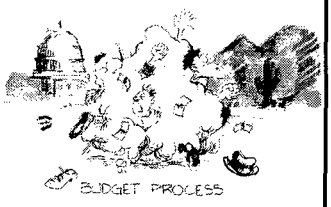


American Stock Exchange

67

## Applications

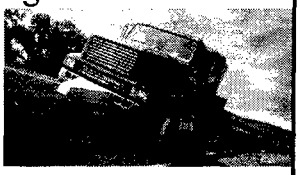
- Investment & new product analysis
- Capital budgeting




68

## Applications

- Investment & new product analysis
- Capital budgeting
- Performance specifications



WesTrack

69

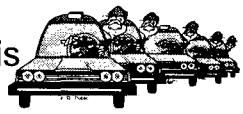
## Applications

- Investment & new product analysis
- Capital budgeting
- Performance specifications
- Quality control

70

## Applications

- Investment & new product analysis
- Capital budgeting
- Performance specifications
- Quality control
- Traffic flow analysis



71

## Applications

- Investment & new product analysis
- Capital budgeting
- Perf. spec. & quality control
- Traffic flow analysis
- Engineering design

***Performance Database***

Future Pavement Condition

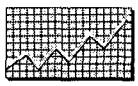
72

## Example: Flexible Pavement Design

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

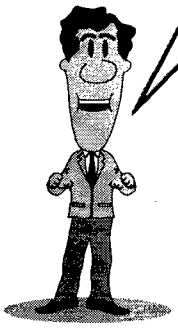
73

## Disadvantages



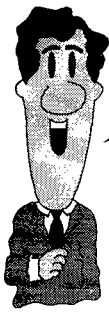
- Computer intensive
  - Proprietary software
  - Complex models
- Requires some statistical background
- Requires "buy-in" of risk management by senior executives

74



This won't work!
You've got to have data to develop those distributions.

75



Its easier to estimate a "range" than a single "point" value.

76

## Advantages

- Quantify risk
- Provide decisionmaker the opportunity to take mitigating action
- Justify budget requests, pavement structural designs, …
- Scenario analysis to create better alternatives

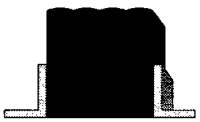
77

## Advantages Con't

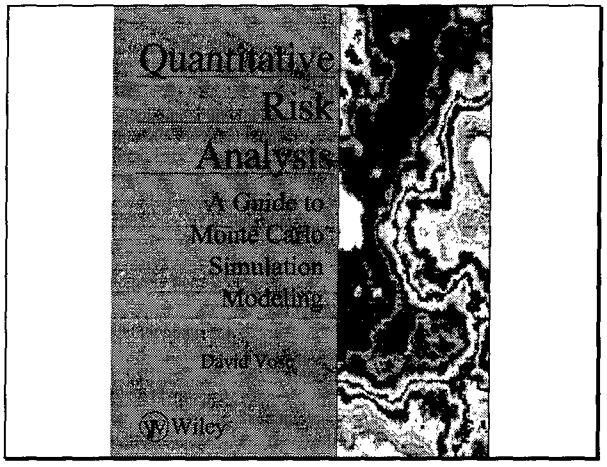
- Elevates the LCCA debate ...
  - From validity of results
  - To what is "our" best policy

78

## Additional Resources

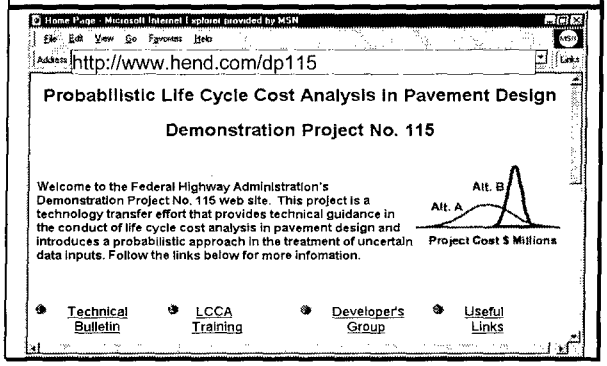


79




80

## DP 115 Web Site

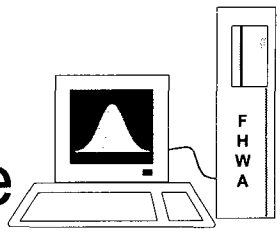



81

## End Session

1

# Software Demonstration




2

## Session Overview

Part 1

- Adding Uncertainty to Models

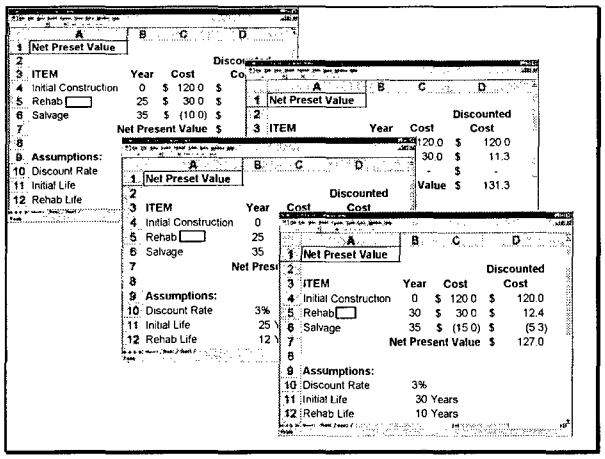
Part 2

- Running a Risk Analysis
- @Risk Results

3

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **Net Preset Value** | | | |
| 2 | | | | **Discounted** |
| 3 | **ITEM** | **Year** | **Cost** | **Cost** |
| 4 | Initial Construction | 0 | $ 120.0 | $ 120.0 |
| 5 | Rehab | 30 | $ 30.0 | $ 12.4 |
| 6 | Salvage | 35 | $ (15.0) | $ (5.3) |
| 7 | | **Net Present Value** | | $ 127.0 |
| 8 | | | | |
| 9 | **Assumptions:** | | | |
| 10 | Discount Rate | 3% | | |
| 11 | Initial Life | 30 Years | | |
| 12 | Rehab Life | 10 Years | | |

4




5

NPV = $132 NPV = $150 NPV = $97 NPV = 123 NPV = $76 NPV = $200 NPV = $156 NPV = $148 NPV = $45 NPV = $187 NPV = ($156) NPV = $286 NPV = $98 NPV = $34 NPV = $165 NPV = $ 6 NPV = $129 NP 47 NPV = $27 NPV 175 NPV = $145 = ($94) NPV = $ 4) NPV = $190 NPV = $167 NPV = $10 NPV = $132 NPV = $88 NPV = $98 NPV = $44 NPV = $22 NPV = $50 NPV = $65 NPV =$90 NPV = $22 NPV = $50 NPV = $65 NPV =$90

Help!

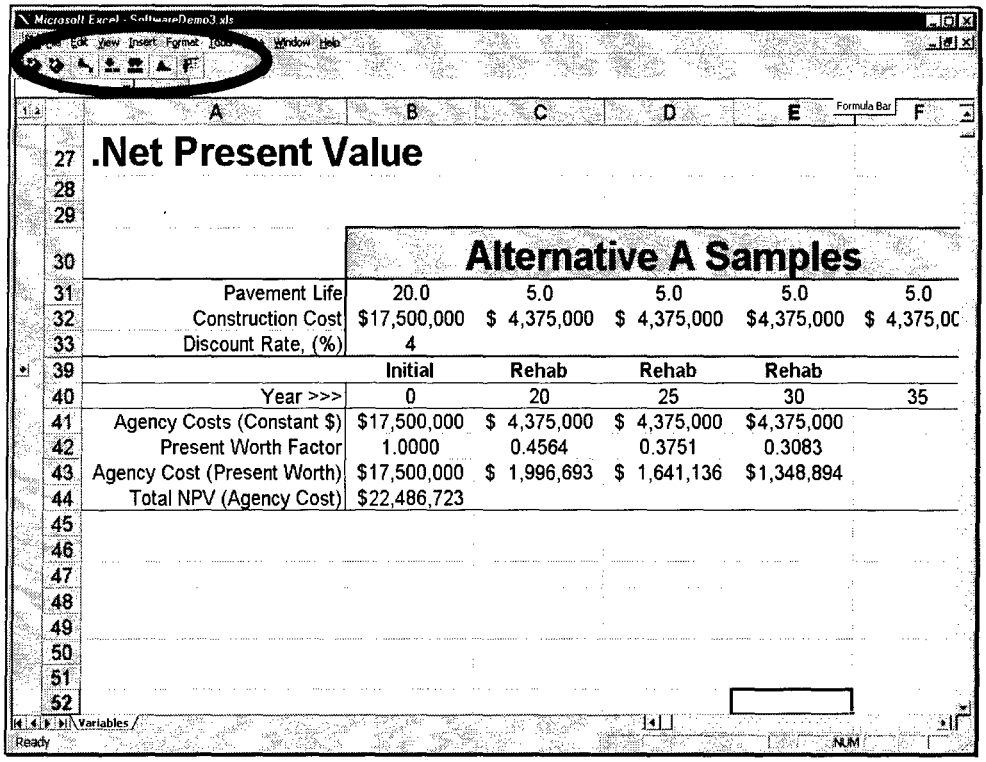
6

## *Solution:* Modeling Uncertainty with Probability

@Risk works with Excel or Lotus

- How to add risk analysis to spreadsheet models
- How to use built-in @Risk functions

7

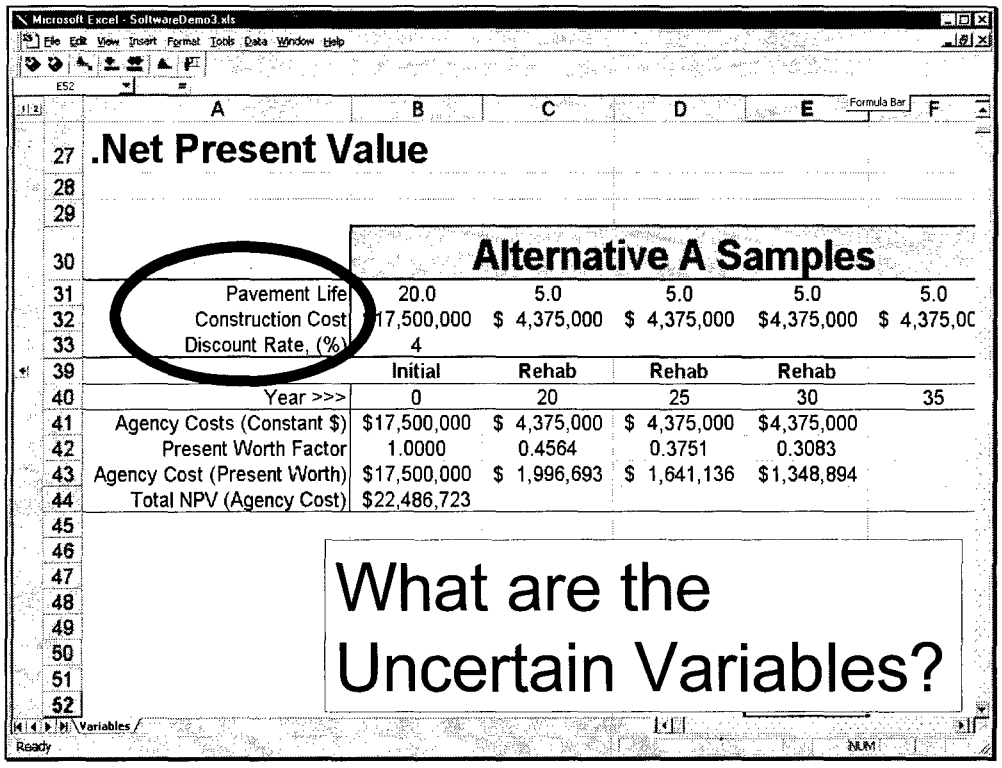



8

## Adding Variability to Spreadsheet Models

- Identify uncertain variables

9




10

Adding Variability to Spreadsheet Models

- Identify uncertain variables
- Describe uncertain variables as probability distributions

11

## Adding Variability to Spreadsheet Models

- Identify uncertain variables
- Describe uncertain variables as probability distributions
- @Risk provides over 30 built-in probability functions

12

## @Risk Probability Functions

| | | |
|---|---|---|
| Beta | Gamma | **Normal** |
| Binomial | Geometric | Pareto |
| Chi-Square | General | Poisson |
| **Cumulative** | Histogram | Truncated Exponential |
| Dependent | Hypergeometric | Truncated Lognormal |
| **Discrete** | Independent | Truncated Normal |
| Discrete Uniform | Logistic | **Triangle** |
| Error Function | **Lognormal** | **Trigen** |
| Erlang | Lognormal2 | **Uniform** |
| Exponential | Negative Binomial | Weibull |

13

## Functions are Similar to Excel

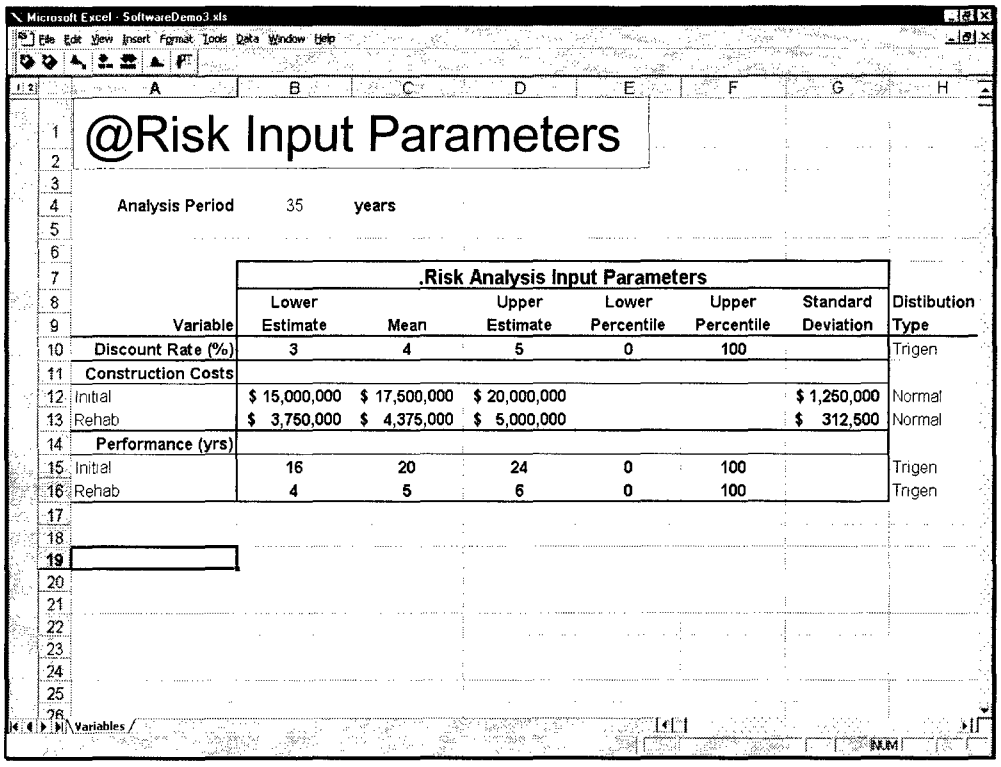
=RiskNormal(A1,A2)

=RiskNormal(3500*B7,C12/3000)

=RiskNormal(RiskLognormal(A1,A2),RiskUniform(1,5))

=If (G7>0,RiskNormal(3500,300),RiskNormal(3500,300*G8))

**14**



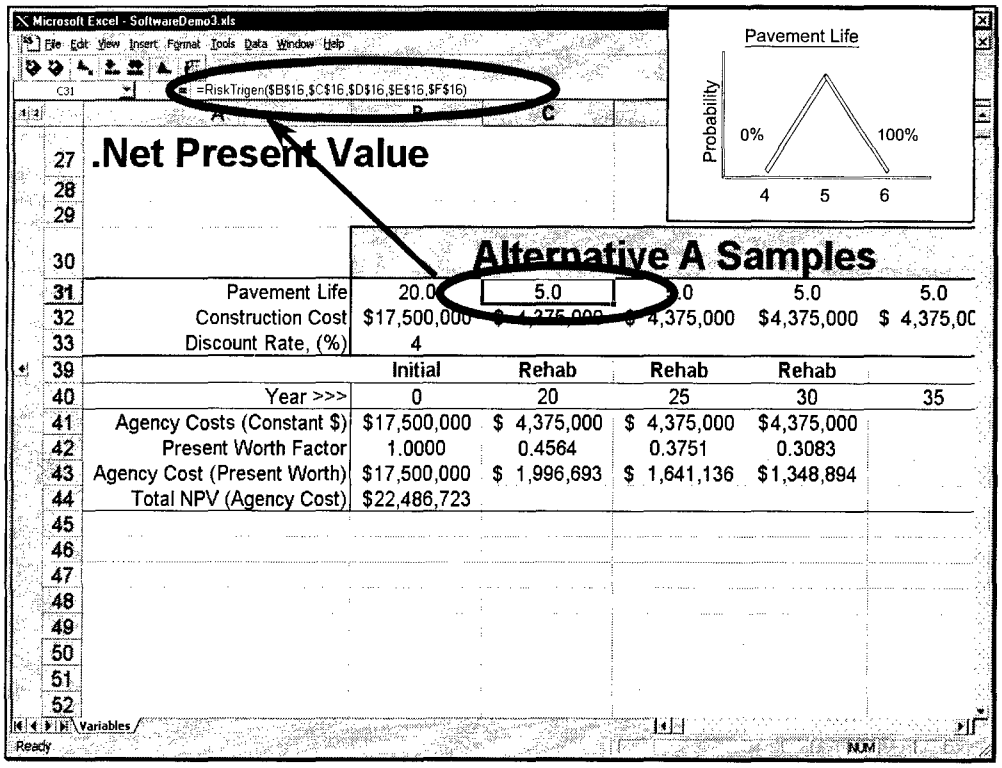
Microsoft Excel - SoftwareDemo3.xls

# @Risk Input Parameters

Analysis Period 35 years

| Variable | .Risk Analysis Input Parameters: Lower Estimate | Mean | Upper Estimate | Lower Percentile | Upper Percentile | Standard Deviation | Distibution Type |
|---|---|---|---|---|---|---|---|
| Discount Rate (%) | 3 | 4 | 5 | 0 | 100 | | Trigen |
| Construction Costs | | | | | | | |
| Initial | $ 15,000,000 | $ 17,500,000 | $ 20,000,000 | | | $ 1,250,000 | Normal |
| Rehab | $ 3,750,000 | $ 4,375,000 | $ 5,000,000 | | | $ 312,500 | Normal |
| Performance (yrs) | | | | | | | |
| Initial | 16 | 20 | 24 | 0 | 100 | | Trigen |
| Rehab | 4 | 5 | 6 | 0 | 100 | | Trigen |

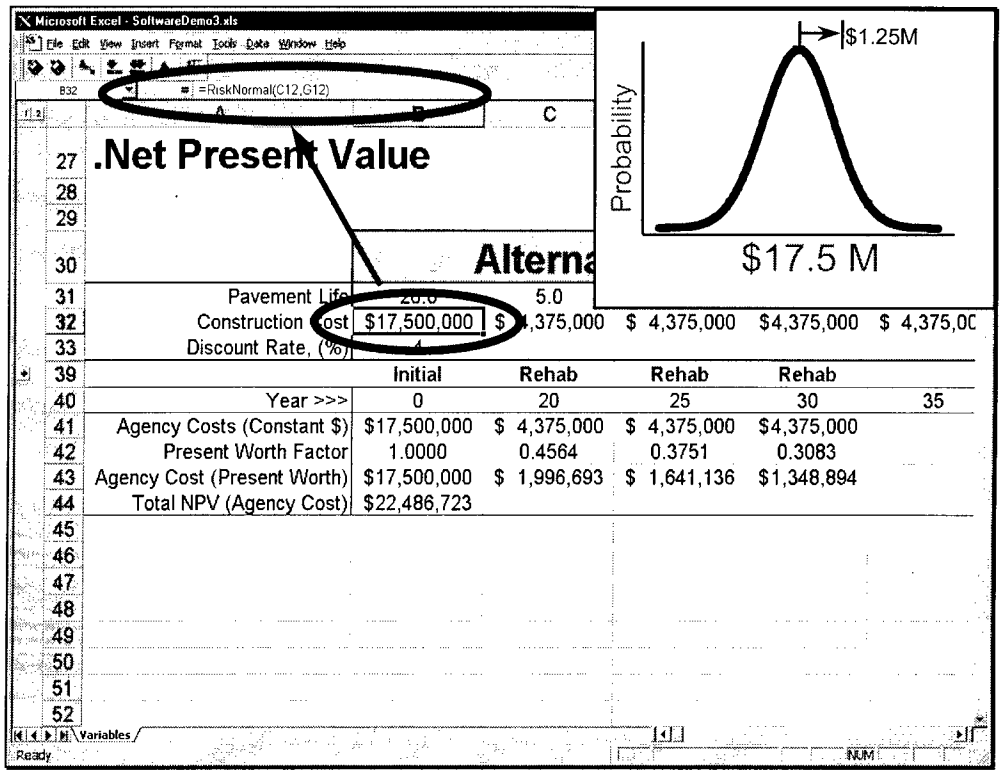
**15**



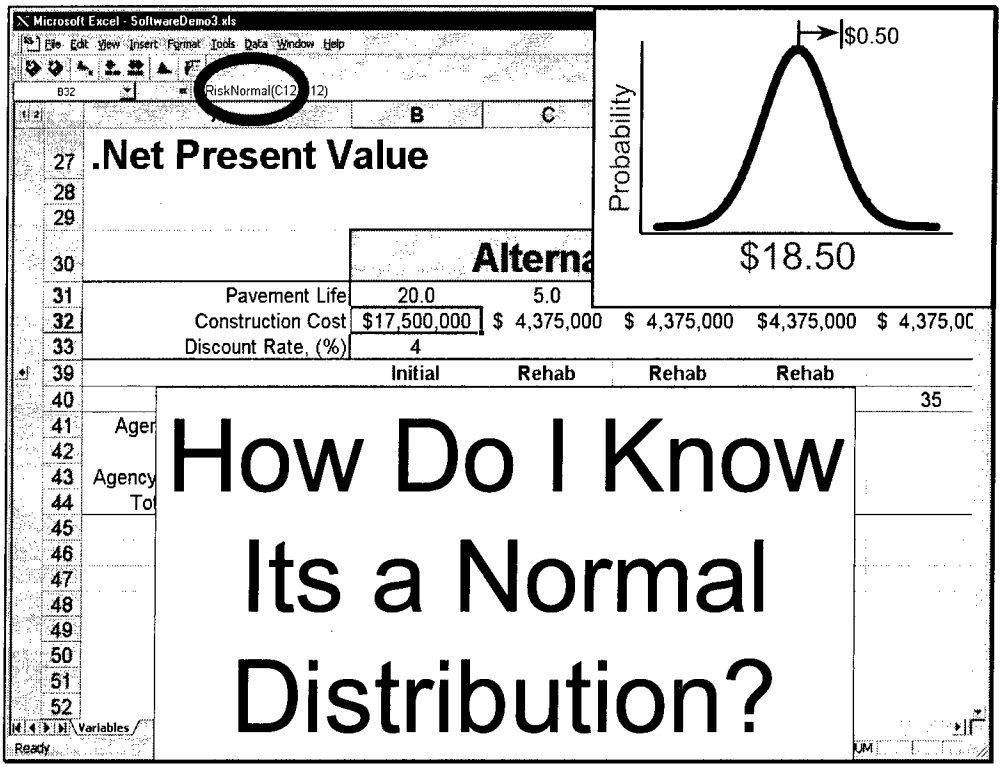

## .Net Present Value

| | Alternative A Samples | | | | |
|---|---|---|---|---|---|
| Pavement Life | 20.0 | 5.0 | .0 | 5.0 | 5.0 |
| Construction Cost | $17,500,000 | $ 4,375,000 | $ 4,375,000 | $4,375,000 | $ 4,375,00 |
| Discount Rate, (%) | 4 | | | | |
| | Initial | Rehab | Rehab | Rehab | |
| Year >>> | 0 | 20 | 25 | 30 | 35 |
| Agency Costs (Constant $) | $17,500,000 | $ 4,375,000 | $ 4,375,000 | $4,375,000 | |
| Present Worth Factor | 1.0000 | 0.4564 | 0.3751 | 0.3083 | |
| Agency Cost (Present Worth) | $17,500,000 | $ 1,996,693 | $ 1,641,136 | $1,348,894 | |
| Total NPV (Agency Cost) | $22,486,723 | | | | |

16


Microsoft Excel - SoftwareDemo3.xls
=RiskNormal(C12,G12)
.Net Present Value
Alterna
Pavement Life 20.0 5.0
Construction Cost $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000 $ 4,375,00
Discount Rate, (%) 4
Initial Rehab Rehab Rehab
Year >>> 0 20 25 30 35
Agency Costs (Constant $) $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000
Present Worth Factor 1.0000 0.4564 0.3751 0.3083
Agency Cost (Present Worth) $17,500,000 $ 1,996,693 $ 1,641,136 $1,348,894
Total NPV (Agency Cost) $22,486,723
Variables
Ready
NUM
$1.25M
Probability
$17.5 M

17


Microsoft Excel - SoftwareDemo3.xls
RiskNormal(C12,G12)
.Net Present Value
Alterna
Pavement Life 20.0 5.0
Construction Cost $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000 $ 4,375,00
Discount Rate, (%) 4
Initial Rehab Rehab Rehab
35
How Do I Know Its a Normal Distribution?
Variables
Ready
$0.50
Probability
$18.50

18

## @Risk Probability Functions

| | | |
|---|---|---|
| Beta | Gamma | Normal |
| Binomial | Geometric | Pareto |
| Chi-Squa | | |
| Cumulati | | xponential |
| Depende | | ognormal |
| Discrete | | ormal |
| Discrete | | |
| Error Function | Lognormal | Trigen |
| Erlang | Lognormal2 | Uniform |
| Exponential | Negative Binomial | Weibull |

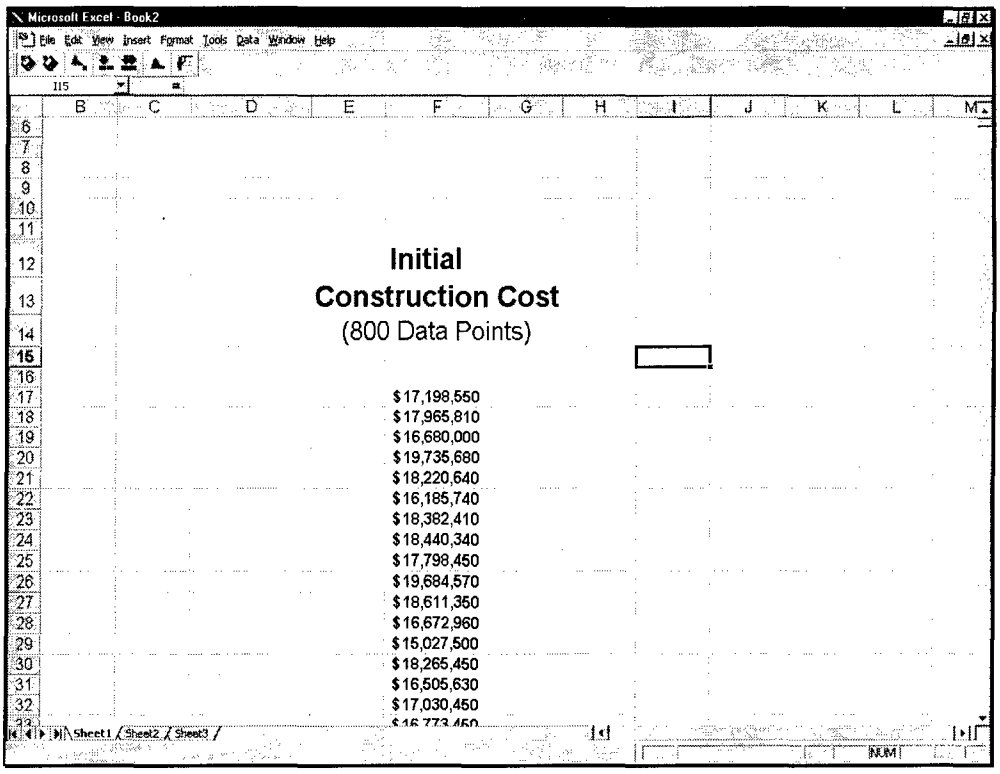
**Which One Should I Use?**

19

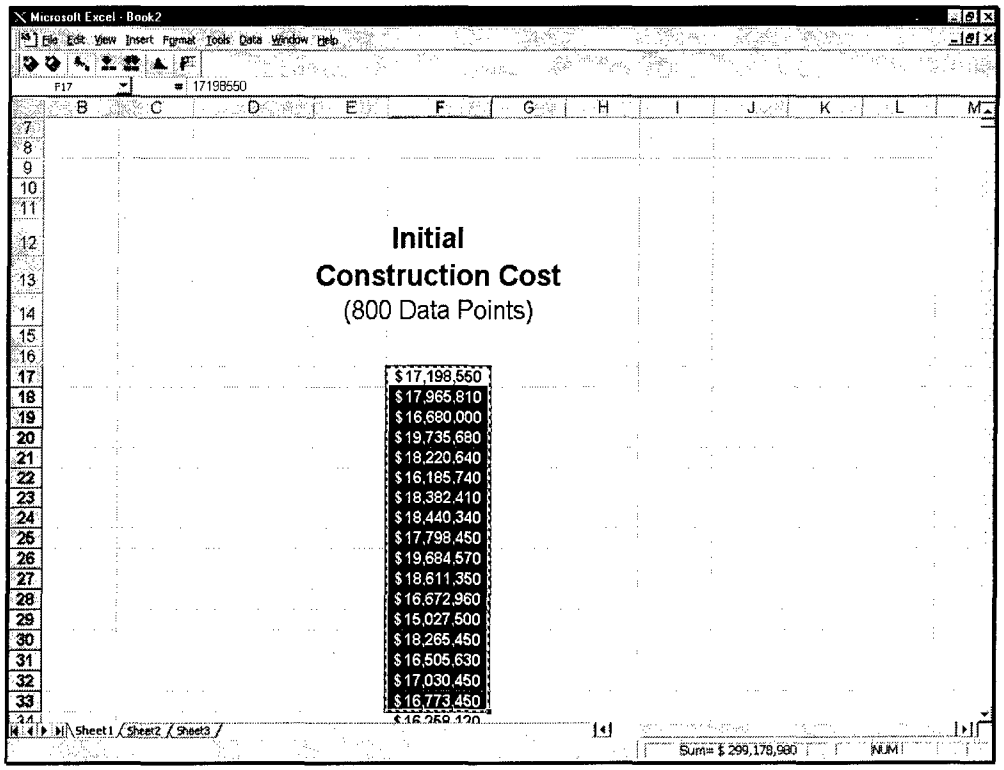
## @Risk & BestFit

- Based on historical data input distribution models are developed using BestFit
- BestFit automatically determines the "bestfit" probability distribution
- Distribution model is "copied" directly into @Risk/Excel spreadsheet

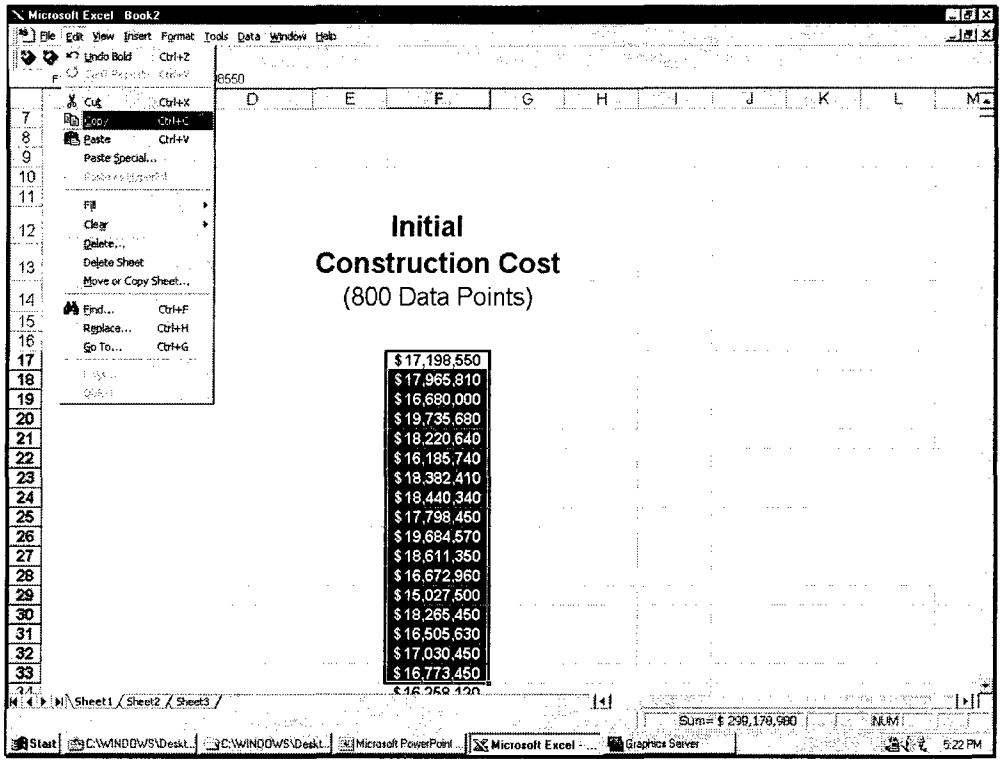
**20**


Microsoft Excel - Book2
Initial
Construction Cost
(800 Data Points)
$17,198,550
$17,965,810
$16,680,000
$19,735,680
$18,220,640
$16,185,740
$18,382,410
$18,440,340
$17,798,450
$19,684,570
$18,611,350
$16,672,960
$15,027,500
$18,265,450
$16,505,630
$17,030,450
Sheet1 Sheet2 Sheet3
NUM

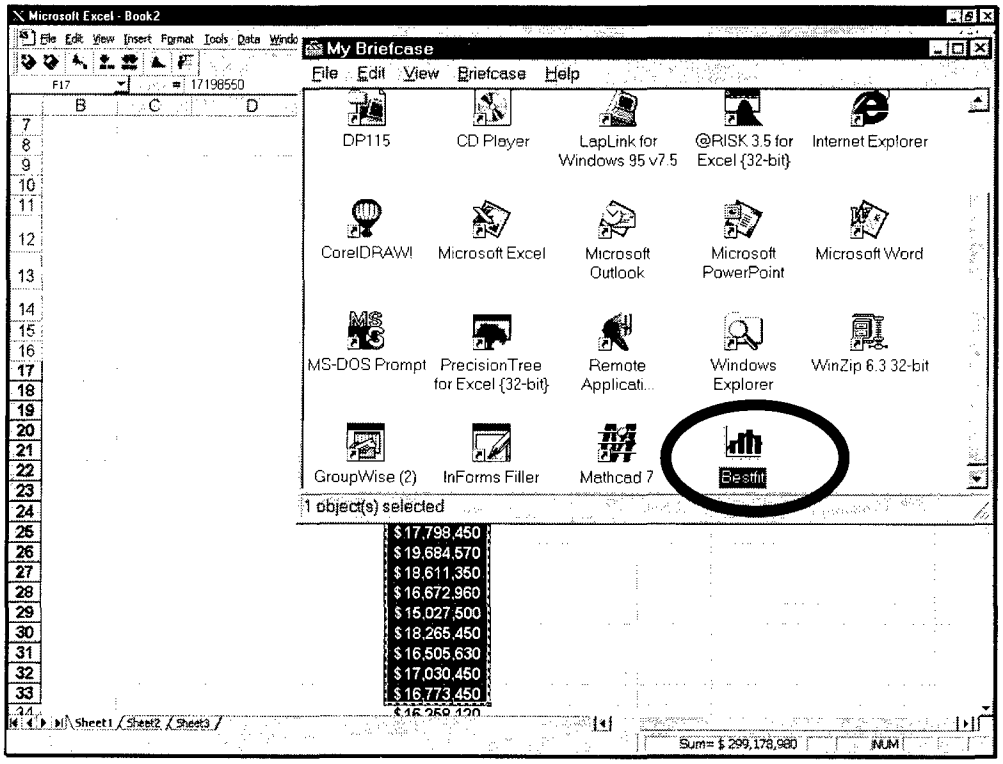
**21**


Microsoft Excel - Book2
F17
17198550
Initial
Construction Cost
(800 Data Points)
$17,198,550
$17,965,810
$16,680,000
$19,735,680
$18,220,640
$16,185,740
$18,382,410
$18,440,340
$17,798,450
$19,684,570
$18,611,350
$16,672,960
$15,027,500
$18,265,450
$16,505,630
$17,030,450
$16,773,450
Sheet1 Sheet2 Sheet3
Sum= $ 299,178,980
NUM

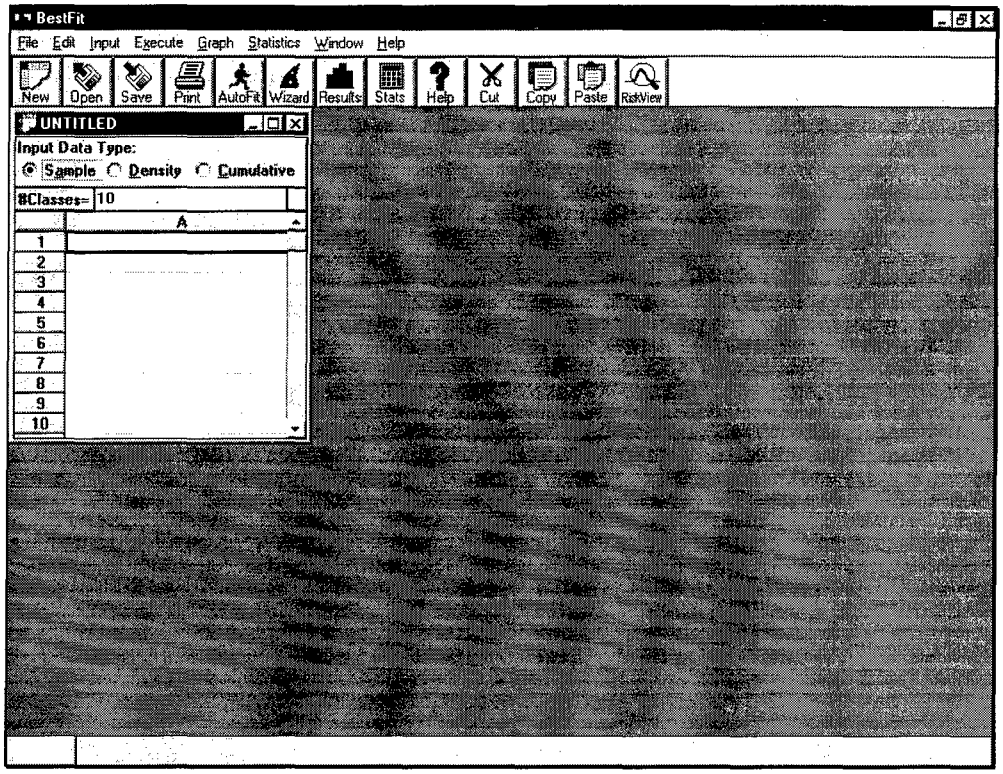
**22**


Microsoft Excel Book2
Initial
Construction Cost
(800 Data Points)
$17,198,550
$17,965,810
$16,680,000
$19,735,680
$18,220,640
$16,185,740
$18,382,410
$18,440,340
$17,798,450
$19,684,570
$18,611,350
$16,672,960
$15,027,500
$18,265,450
$16,505,630
$17,030,450
$16,773,450
Sheet1 Sheet2 Sheet3
Sum= $ 299,178,980
NUM
Start
Microsoft Excel - ...
5:22 PM

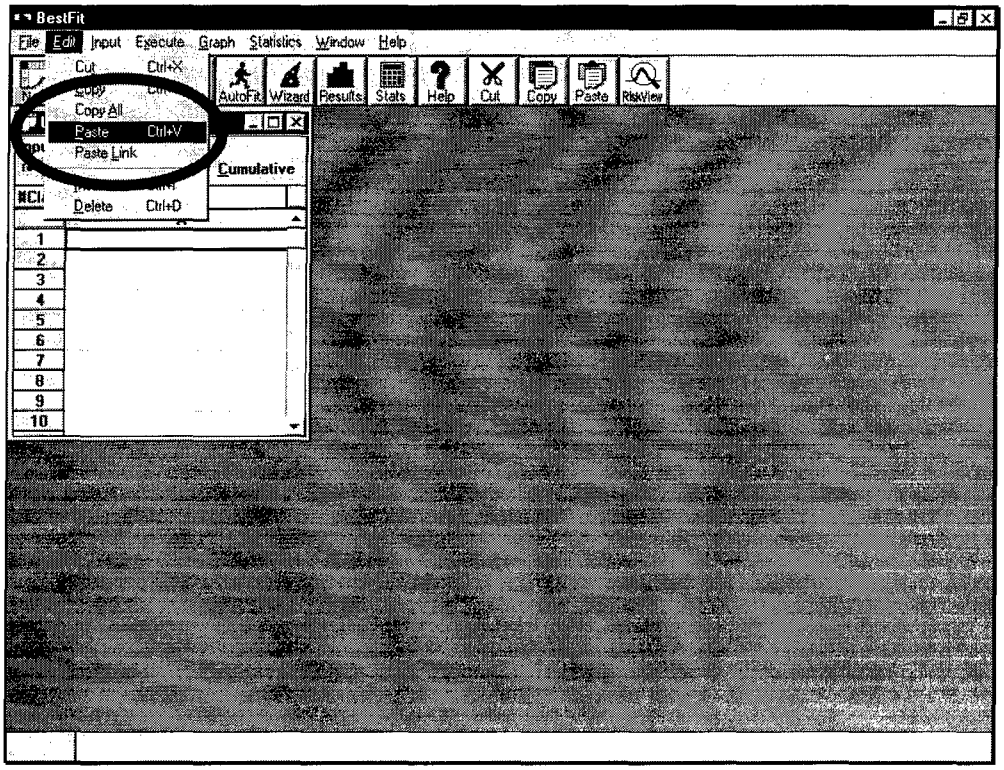
**23**


Microsoft Excel - Book2
My Briefcase
File Edit View Briefcase Help
DP115
CD Player
LapLink for Windows 95 v7.5
@RISK 3.5 for Excel {32-bit}
Internet Explorer
CorelDRAW!
Microsoft Excel
Microsoft Outlook
Microsoft PowerPoint
Microsoft Word
MS-DOS Prompt
PrecisionTree for Excel {32-bit}
Remote Applicati...
Windows Explorer
WinZip 6.3 32-bit
GroupWise (2)
InForms Filler
Mathcad 7
Bestfit
1 object(s) selected
$17,798,450
$19,684,570
$18,611,350
$16,672,960
$15,027,500
$18,265,450
$16,505,630
$17,030,450
$16,773,450
Sheet1 Sheet2 Sheet3
Sum= $ 299,178,980
NUM

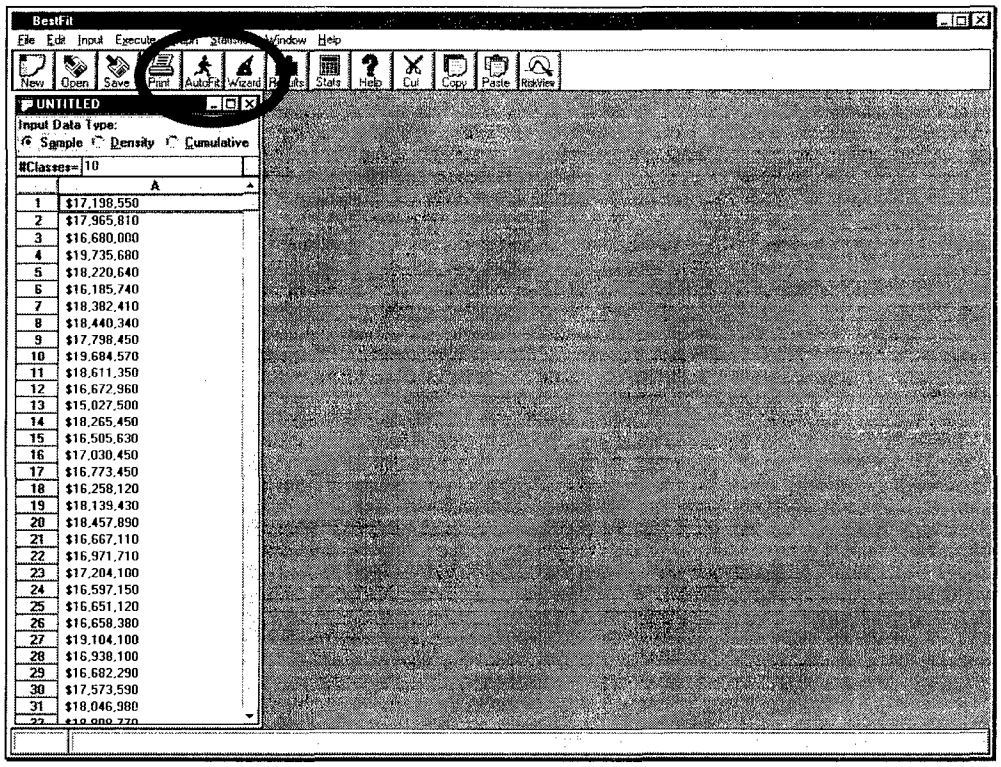
24


BestFit
File Edit Input Execute Graph Statistics Window Help
New Open Save Print AutoFit Wizard Results Stats Help Cut Copy Paste RiskView
UNTITLED
Input Data Type:
Sample Density Cumulative
#Classes= 10
A
1 2 3 4 5 6 7 8 9 10

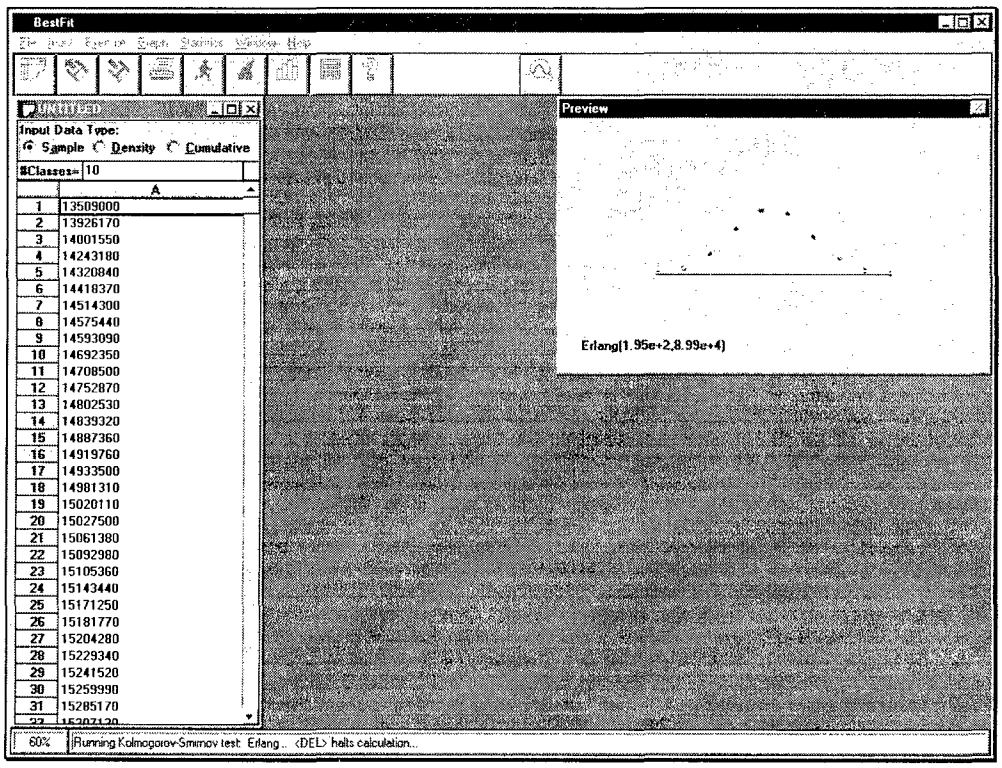
25


BestFit
File Edit Input Execute Graph Statistics Window Help
Cut Ctrl+X
Copy All
Paste Ctrl+V
Paste Link
Delete Ctrl+D
AutoFit Wizard Results Stats Help Cut Copy Paste RiskView
Cumulative
1 2 3 4 5 6 7 8 9 10

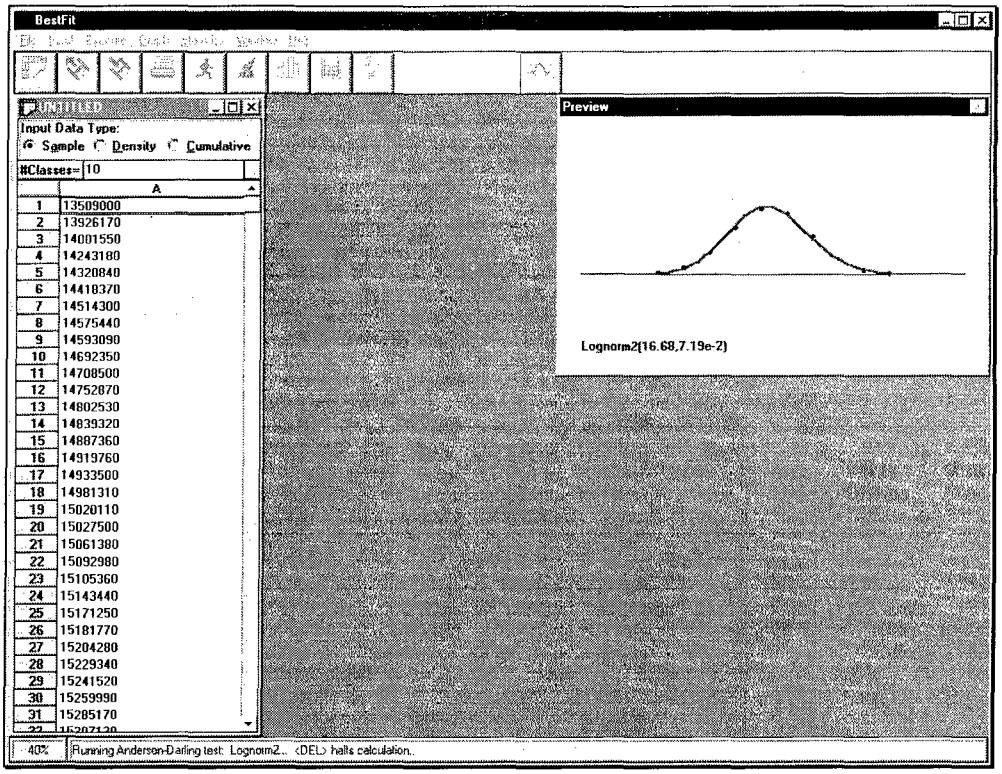
**26**


BestFit
File Edit Input Execute Report Statistics Window Help
New Open Save Print AutoFit Wizard Results Stats Help Cut Copy Paste RiskView
UNTITLED
Input Data Type:
Sample Density Cumulative
#Classes= 10
A
1 $17,198,550
2 $17,965,810
3 $16,680,000
4 $19,735,680
5 $18,220,640
6 $16,185,740
7 $18,382,410
8 $18,440,340
9 $17,798,450
10 $19,684,570
11 $18,611,350
12 $16,672,960
13 $15,027,500
14 $18,265,450
15 $16,505,630
16 $17,030,450
17 $16,773,450
18 $16,258,120
19 $18,139,430
20 $18,457,890
21 $16,667,110
22 $16,971,710
23 $17,204,100
24 $16,597,150
25 $16,651,120
26 $16,658,380
27 $19,104,100
28 $16,938,100
29 $16,682,290
30 $17,573,590
31 $18,046,980

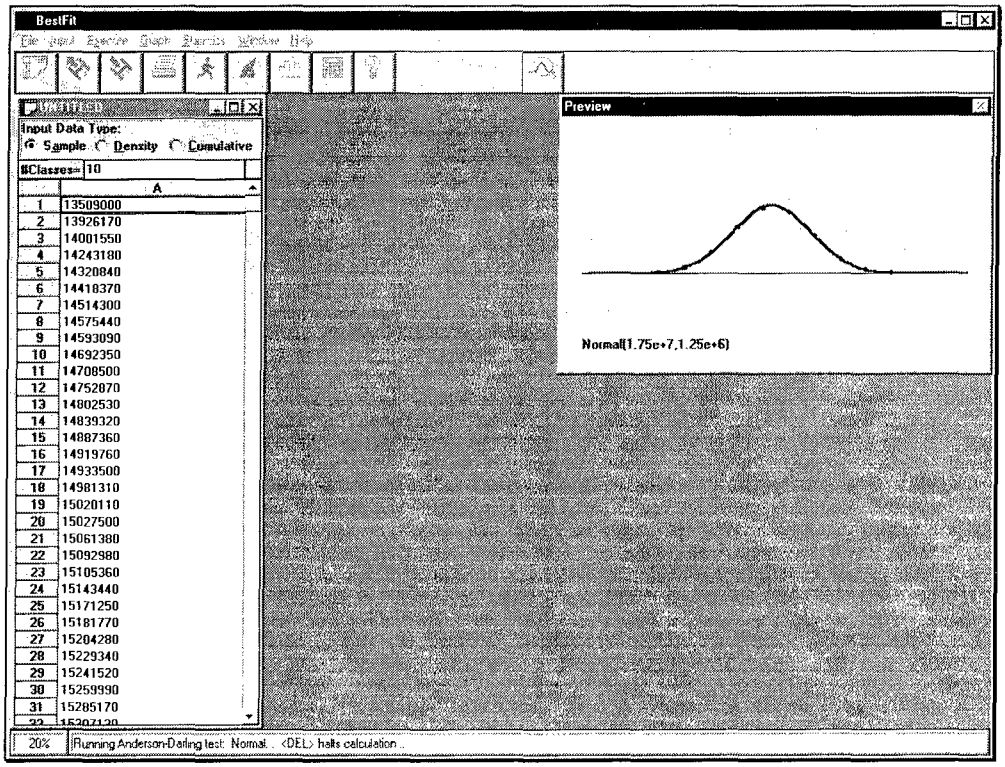
**27**


BestFit
Input Data Type:
Sample Density Cumulative
#Classes= 10
A
1 13509000
2 13926170
3 14001550
4 14243180
5 14320840
6 14418370
7 14514300
8 14575440
9 14593090
10 14692350
11 14708500
12 14752870
13 14802530
14 14839320
15 14887360
16 14919760
17 14933500
18 14981310
19 15020110
20 15027500
21 15061380
22 15092980
23 15105360
24 15143440
25 15171250
26 15181770
27 15204280
28 15229340
29 15241520
30 15259990
31 15285170
Preview
Erlang(1.95e+2,8.99e+4)
50%
Running Kolmogorov-Smirnov test: Erlang... <DEL> halts calculation...

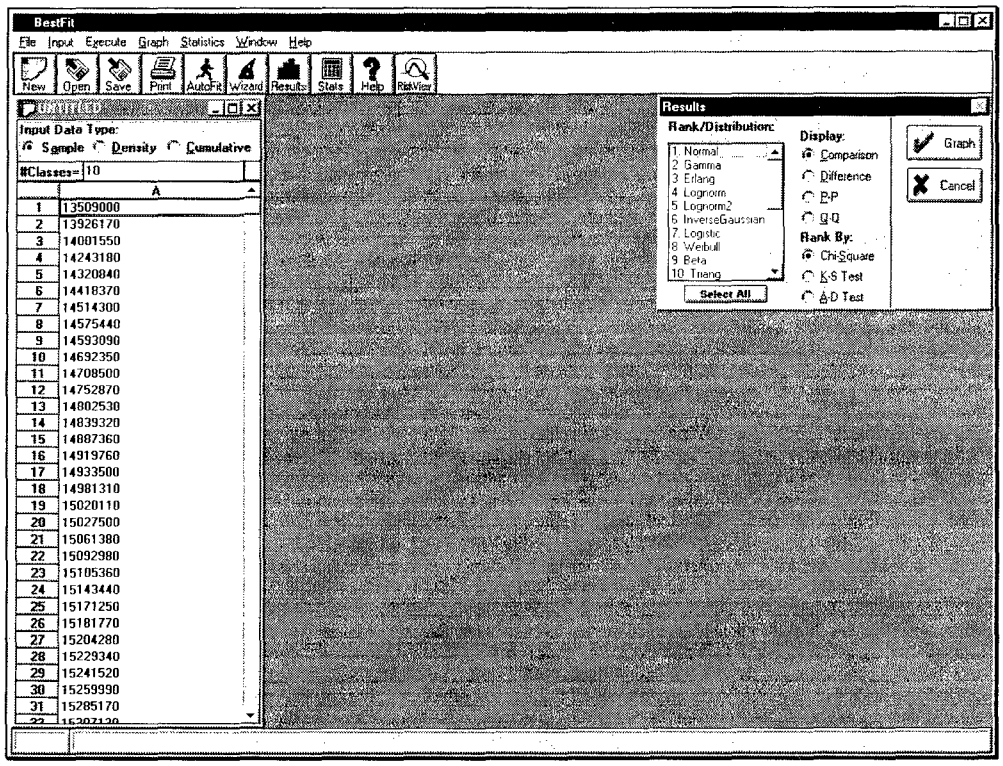
**28**


BestFit
Input Data Type:
Sample Density Cumulative
#Classes= 10
A
1 13509000
2 13926170
3 14001550
4 14243180
5 14320840
6 14418370
7 14514300
8 14575440
9 14593090
10 14692350
11 14708500
12 14752870
13 14802530
14 14839320
15 14887360
16 14919760
17 14933500
18 14981310
19 15020110
20 15027500
21 15061380
22 15092980
23 15105360
24 15143440
25 15171250
26 15181770
27 15204280
28 15229340
29 15241520
30 15259990
31 15285170
Preview
Lognorm2(16.68,7.19e-2)
40%
Running Anderson-Darling test: Lognorm2... <DEL> halts calculation.

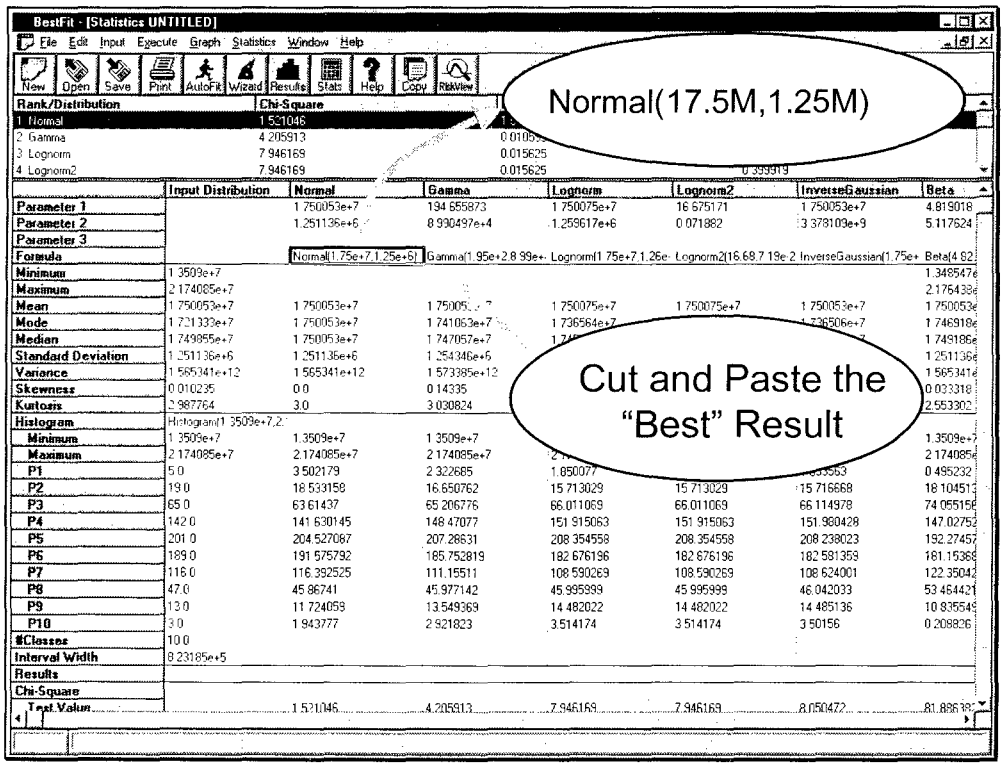
**29**


BestFit
Input Data Type:
Sample Density Cumulative
#Classes= 10
A
1 13509000
2 13926170
3 14001550
4 14243180
5 14320840
6 14418370
7 14514300
8 14575440
9 14593090
10 14692350
11 14708500
12 14752870
13 14802530
14 14839320
15 14887360
16 14919760
17 14933500
18 14981310
19 15020110
20 15027500
21 15061380
22 15092980
23 15105360
24 15143440
25 15171250
26 15181770
27 15204280
28 15229340
29 15241520
30 15259990
31 15285170
Preview
Normal(1.75e+7,1.25e+6)
20%
Running Anderson-Darling test: Normal... <DEL> halts calculation...

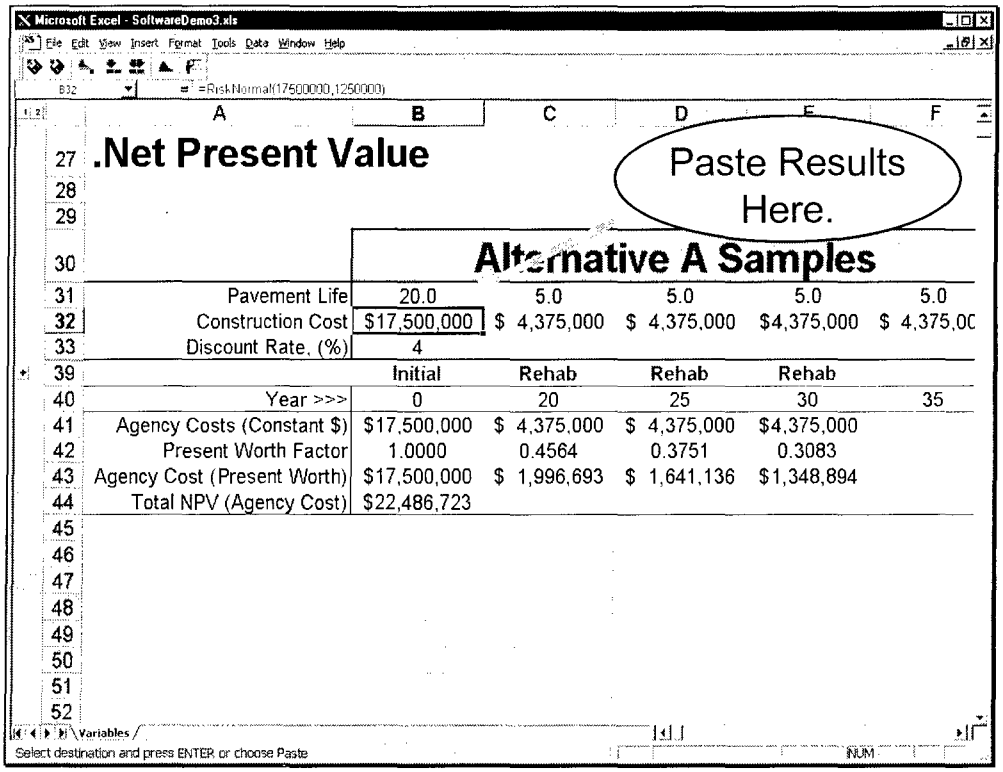
**30**


BestFit
File Input Execute Graph Statistics Window Help
New Open Save Print AutoFit Wizard Results Stats Help RiskView
Input Data Type:
Sample Density Cumulative
#Classes= 10
Results
Rank/Distribution:
1 Normal
2 Gamma
3 Erlang
4 Lognorm
5 Lognorm2
6 InverseGaussian
7 Logistic
8 Weibull
9 Beta
10 Triang
Select All
Display:
Comparison
Difference
P-P
Q-Q
Rank By:
Chi-Square
K-S Test
A-D Test
Graph
Cancel

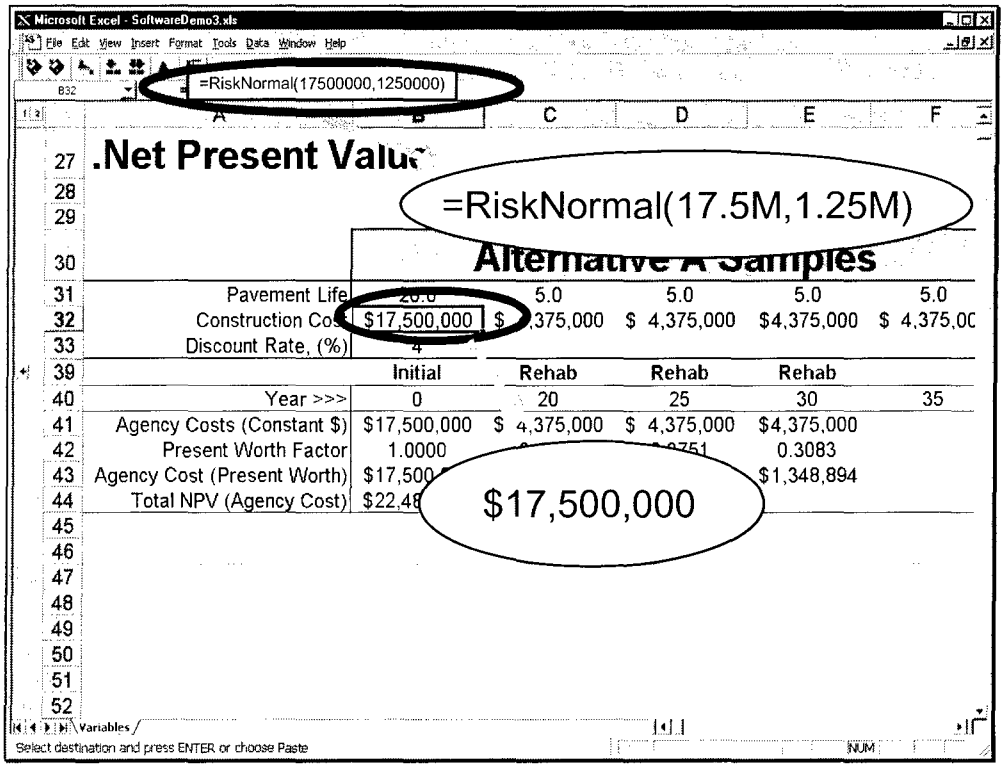
**31**


BestFit - [Statistics UNTITLED]
File Edit Input Execute Graph Statistics Window Help
Normal(17.5M,1.25M)
Cut and Paste the "Best" Result

32


Microsoft Excel - SoftwareDemo3.xls
=RiskNormal(17500000,1250000)
.Net Present Value
Paste Results Here.
Alternative A Samples
Pavement Life 20.0 5.0 5.0 5.0 5.0
Construction Cost $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000 $ 4,375,00
Discount Rate, (%) 4
Initial Rehab Rehab Rehab
Year >>> 0 20 25 30 35
Agency Costs (Constant $) $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000
Present Worth Factor 1.0000 0.4564 0.3751 0.3083
Agency Cost (Present Worth) $17,500,000 $ 1,996,693 $ 1,641,136 $1,348,894
Total NPV (Agency Cost) $22,486,723
Variables
Select destination and press ENTER or choose Paste
NUM

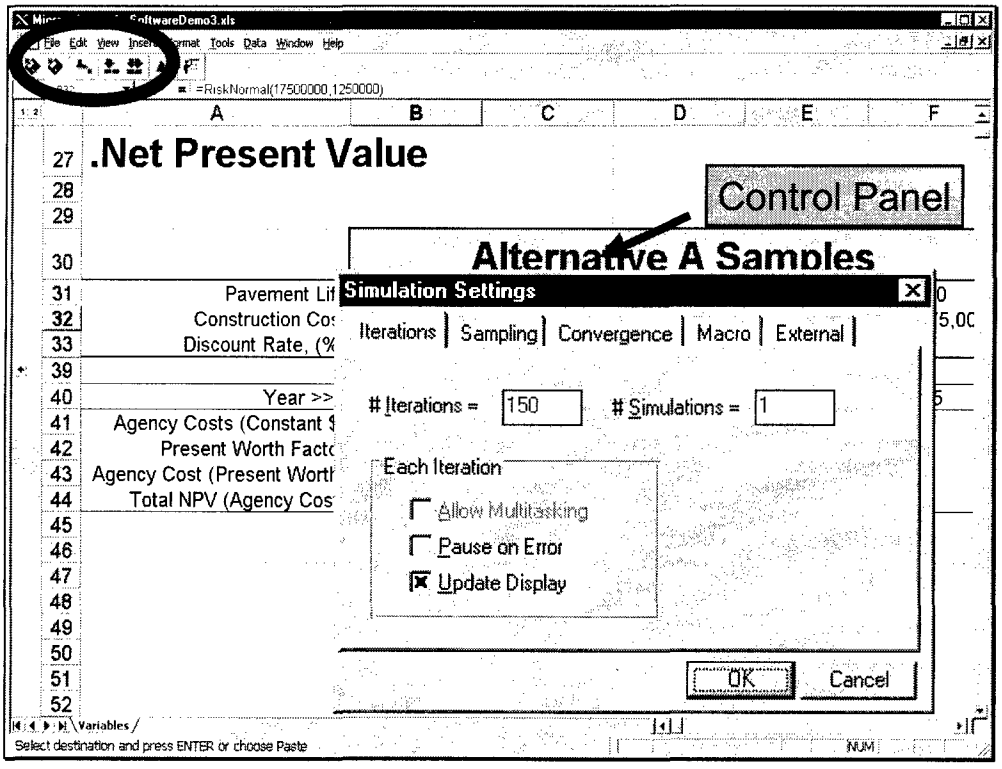
33


Microsoft Excel - SoftwareDemo3.xls
=RiskNormal(17500000,1250000)
.Net Present Valu
=RiskNormal(17.5M,1.25M)
Alternative A Samples
Pavement Life 5.0 5.0 5.0 5.0
Construction Co $17,500,000 $ ,375,000 $ 4,375,000 $4,375,000 $ 4,375,00
Discount Rate, (%) 4
Initial Rehab Rehab Rehab
Year >>> 0 20 25 30 35
Agency Costs (Constant $) $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000
Present Worth Factor 1.0000 0.3083
Agency Cost (Present Worth) $17,500 $1,348,894
Total NPV (Agency Cost) $22,48
$17,500,000
Variables
Select destination and press ENTER or choose Paste
NUM

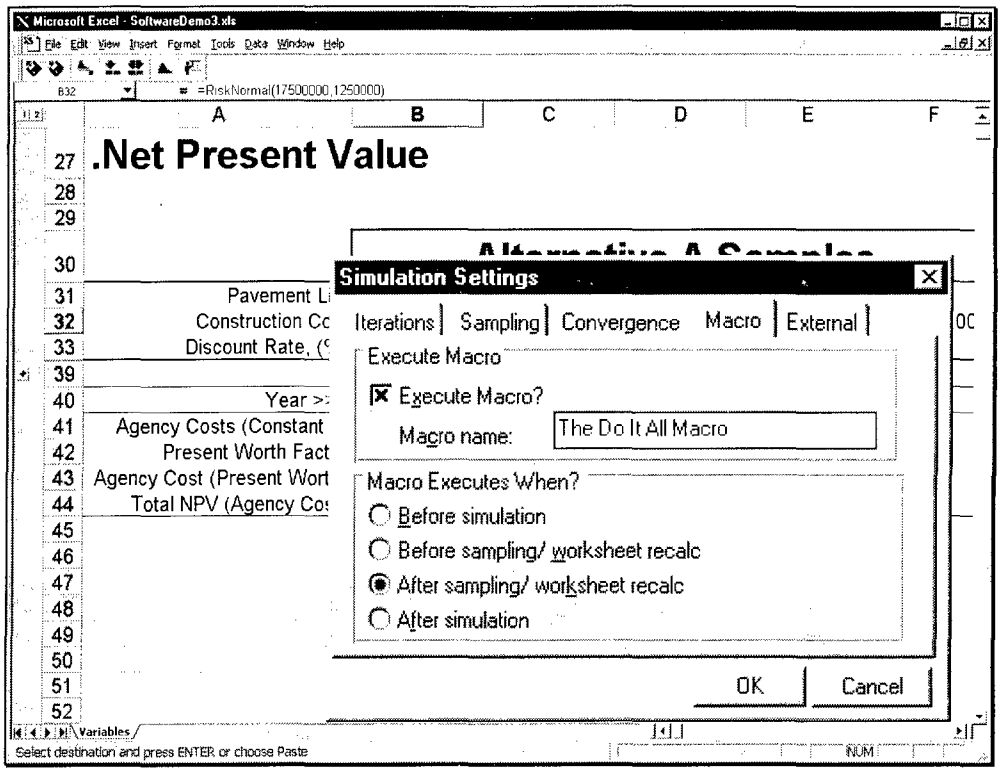
34

## Running a Risk Analysis

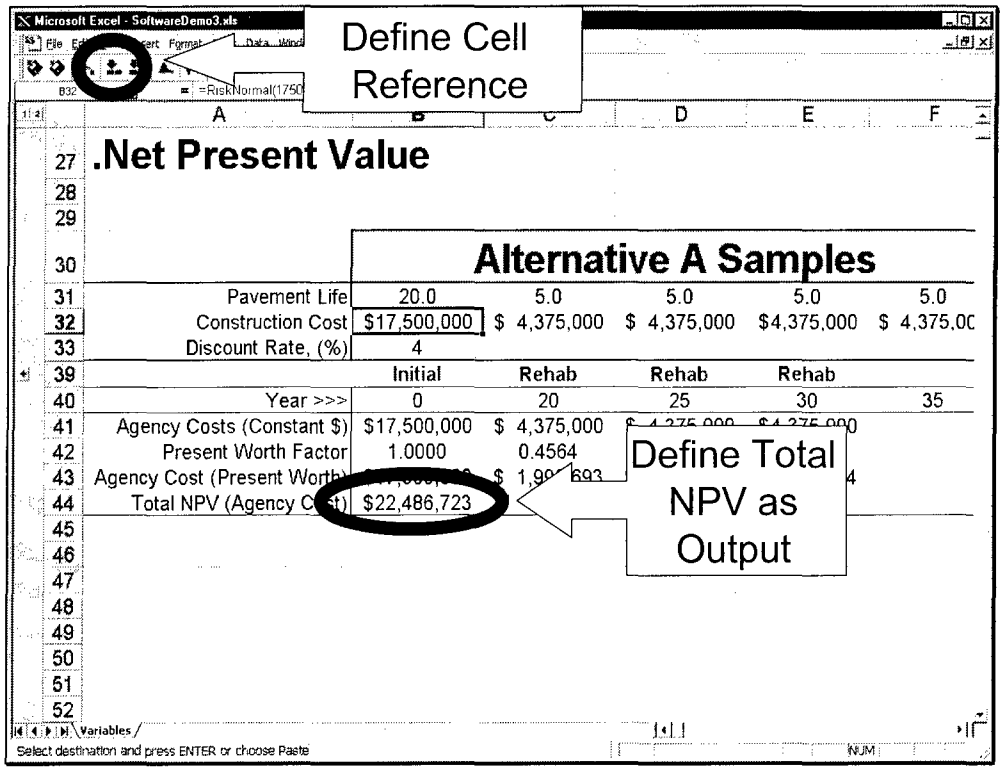
35



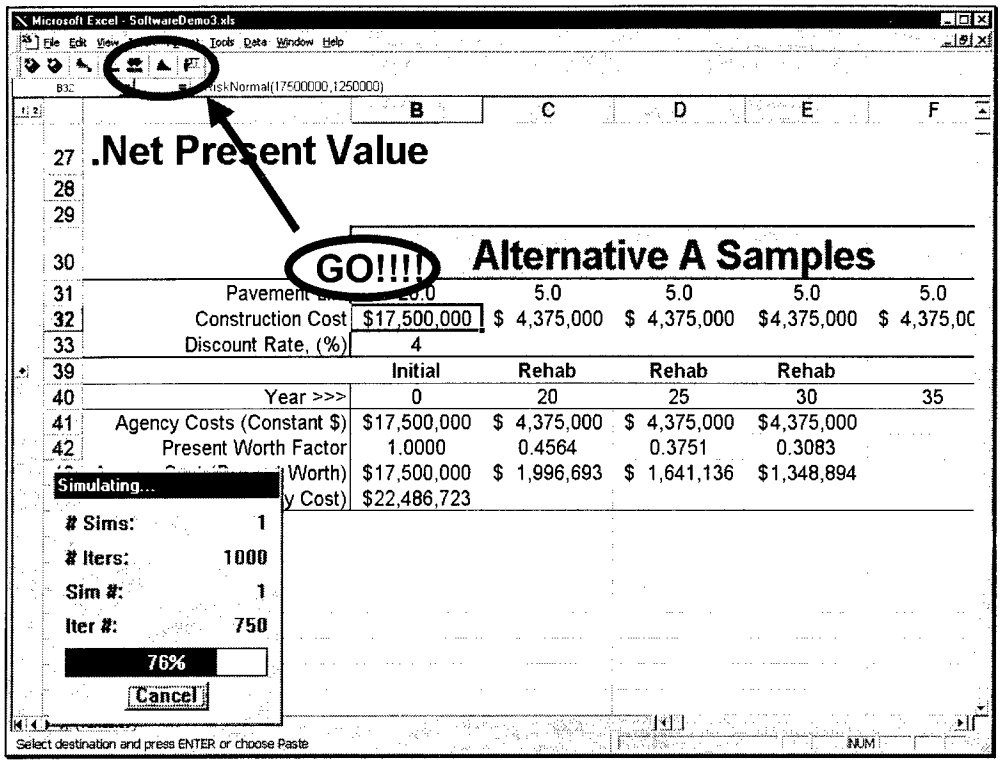
36


Microsoft Excel - SoftwareDemo3.xls
=RiskNormal(17500000,1250000)
.Net Present Value
Simulation Settings
Iterations
Sampling
Convergence
Macro
External
Execute Macro
Execute Macro?
Macro name:
The Do It All Macro
Macro Executes When?
Before simulation
Before sampling/ worksheet recalc
After sampling/ worksheet recalc
After simulation
OK
Cancel
Pavement Li
Construction Cc
Discount Rate, (
Year >>
Agency Costs (Constant
Present Worth Fact
Agency Cost (Present Wort
Total NPV (Agency Co
Variables
Select destination and press ENTER or choose Paste
NUM

37


Define Cell Reference
.Net Present Value
Alternative A Samples
Pavement Life 20.0 5.0 5.0 5.0 5.0
Construction Cost $17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000 $ 4,375,00
Discount Rate, (%) 4
Initial Rehab Rehab Rehab
Year >>> 0 20 25 30 35
Agency Costs (Constant $) $17,500,000 $ 4,375,000
Present Worth Factor 1.0000 0.4564
Total NPV (Agency C $22,486,723
Define Total NPV as Output
Variables
Select destination and press ENTER or choose Paste
NUM

38




39

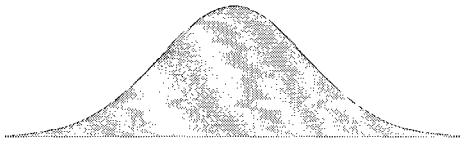
## Simulation Processing

- Latin Hypercube
- 24 Input Variables
- 1 Output Variables
- 10,000 Iterations
- Run Time = 1 minute 15 seconds

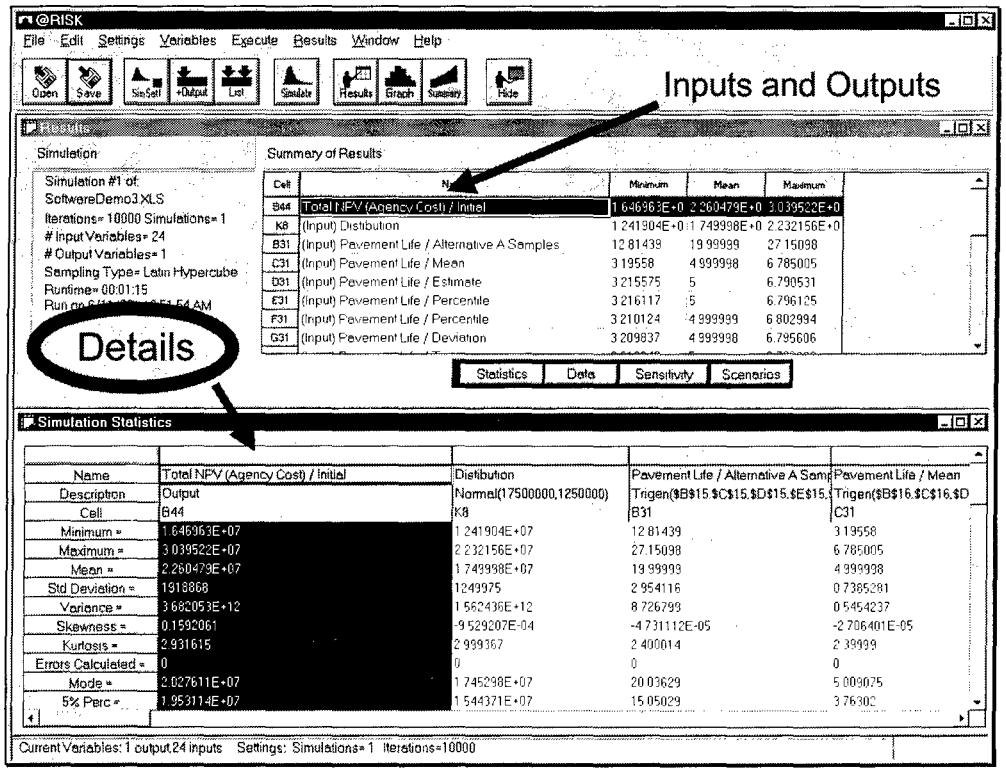
40

## Simulation Results

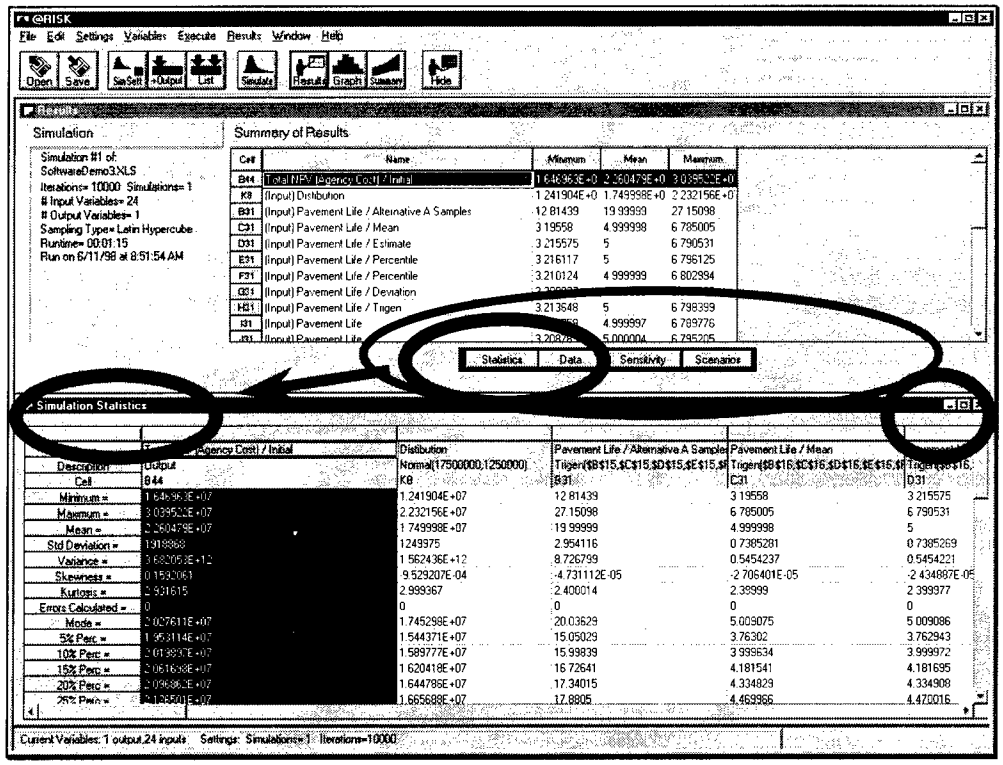
- Results from each iteration are stored and presented as probability distributions.



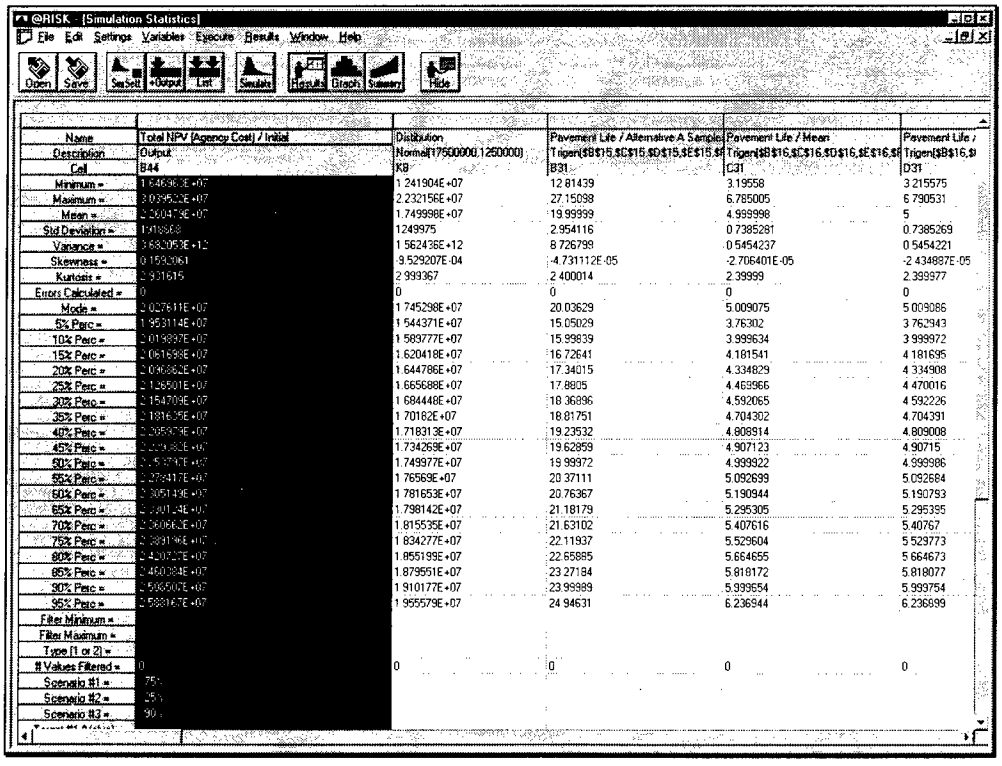
41



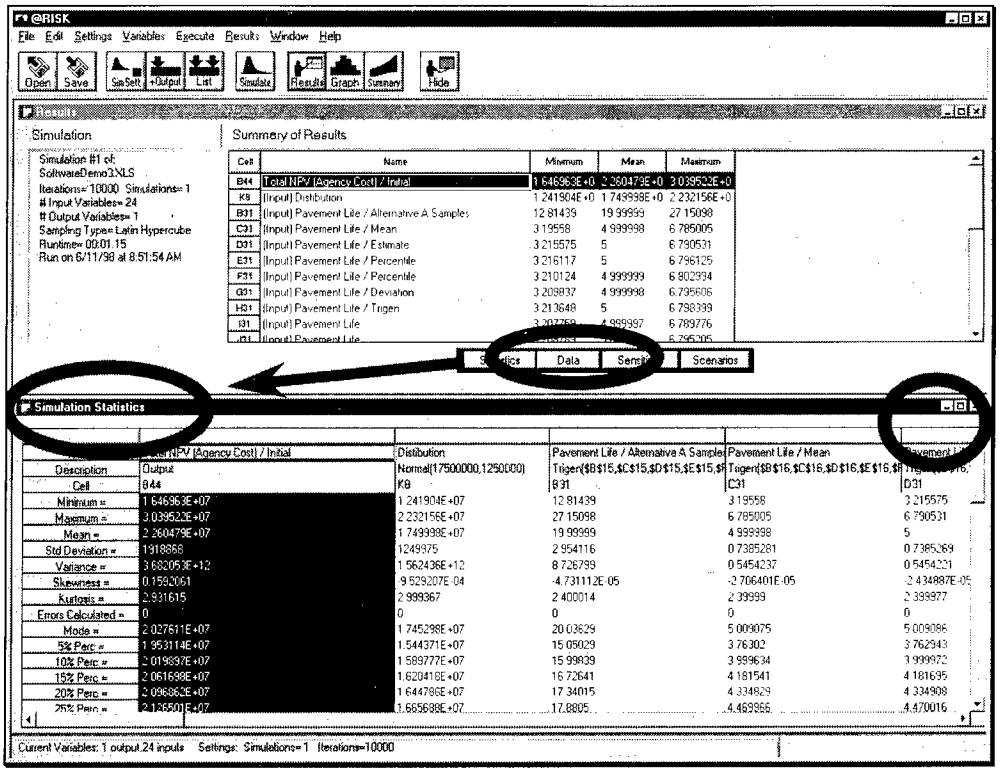
**42**


@RISK
File Edit Settings Variables Execute Results Window Help
Open Save SaSett +Output List Simulate Results Graph Summary Hide
Results
Simulation
Summary of Results
Simulation #1 of SoftwareDemo3.XLS
Iterations= 10000 Simulations= 1
# Input Variables= 24
# Output Variables= 1
Sampling Type= Latin Hypercube
Runtime= 00:01:15
Run on 6/11/98 at 8:51:54 AM
Cell Name Minimum Mean Maximum
B44 Total NPV (Agency Cost) / Initial 1.646963E+0 2.260478E+0 3.039522E+0
K8 (Input) Distribution 1.241904E+0 1.749998E+0 2.232156E+0
B31 (Input) Pavement Life / Alternative A Samples 12.81439 19.99999 27.15098
C31 (Input) Pavement Life / Mean 3.19558 4.999998 6.785005
D31 (Input) Pavement Life / Estimate 3.215575 5 6.790531
E31 (Input) Pavement Life / Percentile 3.216117 5 6.796125
F31 (Input) Pavement Life / Percentile 3.210124 4.999999 6.802984
G31 (Input) Pavement Life / Deviation
H31 (Input) Pavement Life / Trigen 3.213648 5 6.799399
I31 (Input) Pavement Life 4.999997 6.799776
Statistics Data Sensitivity Scenarios
Simulation Statistics
Description Output
Cell B44
Minimum = 1.646963E+07
Maximum = 3.039522E+07
Mean = 2.260478E+07
Std Deviation = 1918868
Variance = 3.682053E+12
Skewness = 0.1592061
Kurtosis = 2.931615
Errors Calculated = 0
Mode = 2.027611E+07
5% Perc = 1.953114E+07
10% Perc = 2.019897E+07
15% Perc = 2.061698E+07
20% Perc = 2.096862E+07
25% Perc = 2.126501E+07
Distribution Normal(17500000,1250000) K8
1.241904E+07 1.745298E+07 1.544371E+07 1.589777E+07 1.620418E+07 1.644786E+07 1.665688E+07
Pavement Life / Alternative A Samples Trigen($B$15,$C$15,$D$15,$E$15,$ B31
12.81439 20.03629 15.05029 15.99839 16.72641 17.34015 17.8805
Pavement Life / Mean Trigen($B$16,$C$16,$D$16,$E$16,$ C31
3.19558 5.009075 3.76302 3.999634 4.181541 4.334829 4.469966
Trigen($B$16, D31
3.215575 5.009086 3.762943 3.999972 4.181695 4.334908 4.470016
Current Variables: 1 output,24 inputs Settings: Simulations=1 Iterations=10000

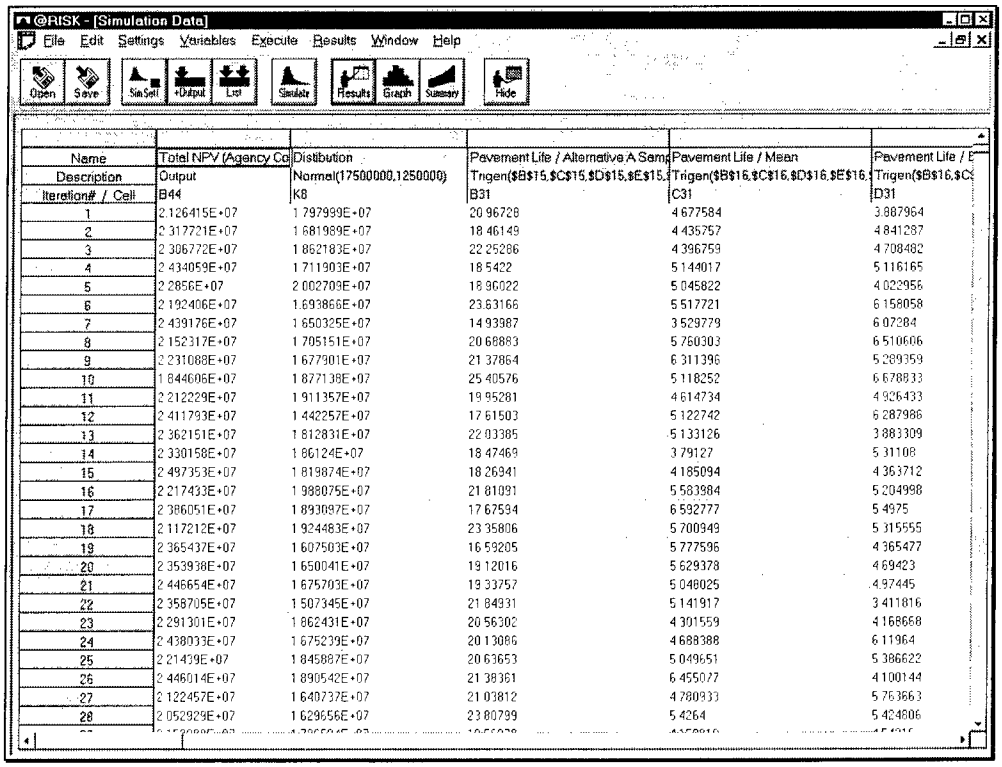
**43**


@RISK - [Simulation Statistics]
File Edit Settings Variables Execute Results Window Help
Open Save SaSett +Output List Simulate Results Graph Summary Hide
Name Total NPV (Agency Cost) / Initial
Description Output
Cell B44
Minimum = 1.646963E+07
Maximum = 3.039522E+07
Mean = 2.260478E+07
Std Deviation = 1918868
Variance = 3.682053E+12
Skewness = 0.1592061
Kurtosis = 2.931615
Errors Calculated = 0
Mode = 2.027611E+07
5% Perc = 1.953114E+07
10% Perc = 2.019897E+07
15% Perc = 2.061698E+07
20% Perc = 2.096862E+07
25% Perc = 2.126501E+07
30% Perc = 2.154709E+07
35% Perc = 2.181635E+07
40% Perc = 2.205979E+07
45% Perc = 2.234268E+07
50% Perc = 2.257907E+07
55% Perc = 2.278417E+07
60% Perc = 2.305149E+07
65% Perc = 2.330134E+07
70% Perc = 2.360863E+07
75% Perc = 2.389196E+07
80% Perc = 2.420727E+07
85% Perc = 2.460084E+07
90% Perc = 2.506500E+07
95% Perc = 2.588167E+07
Filter Minimum =
Filter Maximum =
Type [1 or 2] =
# Values Filtered = 0
Scenario #1 = 75
Scenario #2 = 25
Scenario #3 = 90
Distribution Normal(17500000,1250000) K8
1.241904E+07 1.745998E+07 1.544371E+07 1.589777E+07 1.620418E+07 1.644786E+07 1.665688E+07 1.684448E+07 1.70162E+07 1.718313E+07 1.734269E+07 1.749977E+07 1.76569E+07 1.781653E+07 1.798142E+07 1.815535E+07 1.834277E+07 1.855199E+07 1.879551E+07 1.910177E+07 1.955579E+07
Pavement Life / Alternative A Samples Trigen($B$15,$C$15,$D$15,$E$15,$ B31
12.81439 20.03629 15.05029 15.99839 16.72641 17.34015 17.8805 18.36896 18.81751 19.23532 19.62859 19.99972 20.37111 20.76367 21.18179 21.63102 22.11937 22.65885 23.27184 23.99889 24.94631
Pavement Life / Mean Trigen($B$16,$C$16,$D$16,$E$16,$ C31
3.19558 5.009075 3.76302 3.999634 4.181541 4.334829 4.469966 4.592065 4.704302 4.808914 4.907123 4.999922 5.092699 5.190944 5.295305 5.407616 5.529604 5.664655 5.818172 5.999654 6.236944
Trigen($B$16,$ D31
3.215575 6.790531 5 6.785005 0.7385281 0.5454237 -2.706401E-05 2.399999 0 5.009075 3.762943 3.999972 4.181695 4.334908 4.592226 4.704391 4.809008 4.90715 4.999986 5.092684 5.190793 5.295395 5.40767 5.529773 5.664673 5.818077 5.999754 6.236899

**44**




**45**



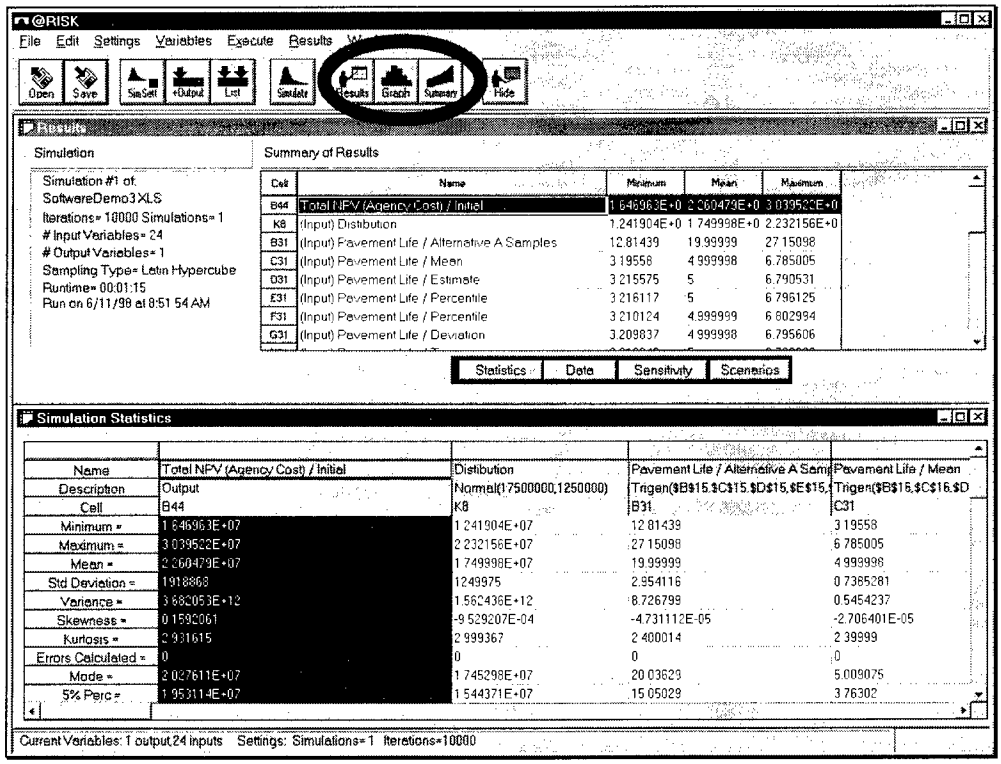

| Name | Total NPV (Agency Co | Distribution | Pavement Life / Alternative A Samp | Pavement Life / Mean | Pavement Life / E |
|---|---|---|---|---|---|
| Description | Output | Normal(17500000,1250000) | Trigen($B$15,$C$15,$D$15,$E$15,$ | Trigen($B$16,$C$16,$D$16,$E$16,$ | Trigen($B$16,$C$ |
| Iteration# / Cell | B44 | K8 | B31 | C31 | D31 |
| 1 | 2.126415E+07 | 1.797999E+07 | 20.96728 | 4.677584 | 3.887964 |
| 2 | 2.317721E+07 | 1.681989E+07 | 18.46149 | 4.435757 | 4.841287 |
| 3 | 2.306772E+07 | 1.862183E+07 | 22.25286 | 4.396759 | 4.708482 |
| 4 | 2.434059E+07 | 1.711903E+07 | 18.5422 | 5.144017 | 5.116165 |
| 5 | 2.2856E+07 | 2.002709E+07 | 18.96022 | 5.045822 | 4.022956 |
| 6 | 2.192406E+07 | 1.693866E+07 | 23.63166 | 5.517721 | 6.158058 |
| 7 | 2.439176E+07 | 1.650325E+07 | 14.93987 | 3.529779 | 6.07284 |
| 8 | 2.152317E+07 | 1.705151E+07 | 20.68883 | 5.760303 | 6.510606 |
| 9 | 2.231088E+07 | 1.677901E+07 | 21.37864 | 6.311396 | 5.289359 |
| 10 | 1.844606E+07 | 1.877138E+07 | 25.40576 | 5.118252 | 6.678833 |
| 11 | 2.212229E+07 | 1.911357E+07 | 19.95281 | 4.614734 | 4.926433 |
| 12 | 2.411793E+07 | 1.442257E+07 | 17.61503 | 5.122742 | 6.287986 |
| 13 | 2.362151E+07 | 1.812831E+07 | 22.03385 | 5.133126 | 3.883309 |
| 14 | 2.330158E+07 | 1.86124E+07 | 18.47469 | 3.79127 | 5.31108 |
| 15 | 2.497353E+07 | 1.819874E+07 | 18.26941 | 4.185094 | 4.363712 |
| 16 | 2.217433E+07 | 1.988075E+07 | 21.81091 | 5.583984 | 5.204998 |
| 17 | 2.386051E+07 | 1.893097E+07 | 17.67594 | 6.592777 | 5.4975 |
| 18 | 2.117212E+07 | 1.924483E+07 | 23.35806 | 5.700949 | 5.315555 |
| 19 | 2.365437E+07 | 1.607503E+07 | 16.59205 | 5.777596 | 4.365477 |
| 20 | 2.353938E+07 | 1.650041E+07 | 19.12016 | 5.629378 | 4.69423 |
| 21 | 2.446654E+07 | 1.675703E+07 | 19.33757 | 5.048025 | 4.97445 |
| 22 | 2.358705E+07 | 1.507345E+07 | 21.84931 | 5.141917 | 3.411816 |
| 23 | 2.291301E+07 | 1.862431E+07 | 20.56302 | 4.301559 | 4.168668 |
| 24 | 2.438033E+07 | 1.675239E+07 | 20.13086 | 4.688388 | 6.11964 |
| 25 | 2.21439E+07 | 1.845887E+07 | 20.63653 | 5.049651 | 5.386622 |
| 26 | 2.446014E+07 | 1.890542E+07 | 21.38361 | 6.455077 | 4.100144 |
| 27 | 2.122457E+07 | 1.640737E+07 | 21.03812 | 4.780833 | 5.763663 |
| 28 | 2.052929E+07 | 1.629656E+07 | 23.80799 | 5.4264 | 5.424806 |

**46**

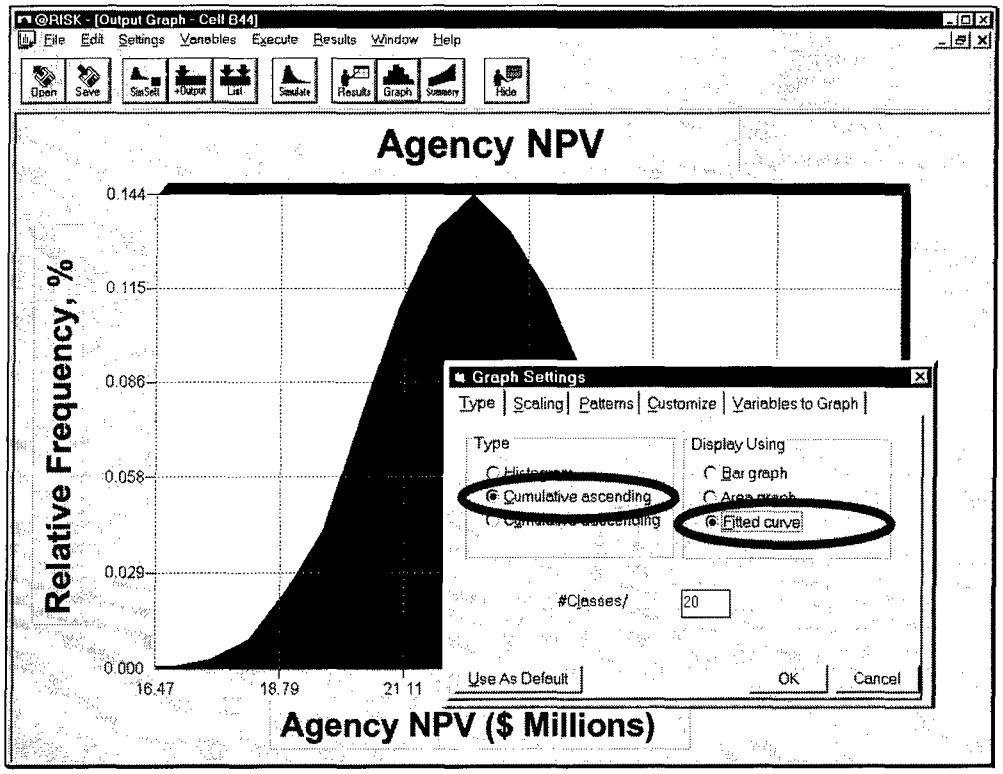
## Agency NPV

- Probability
- Sensitivity
- Scenario Analysis

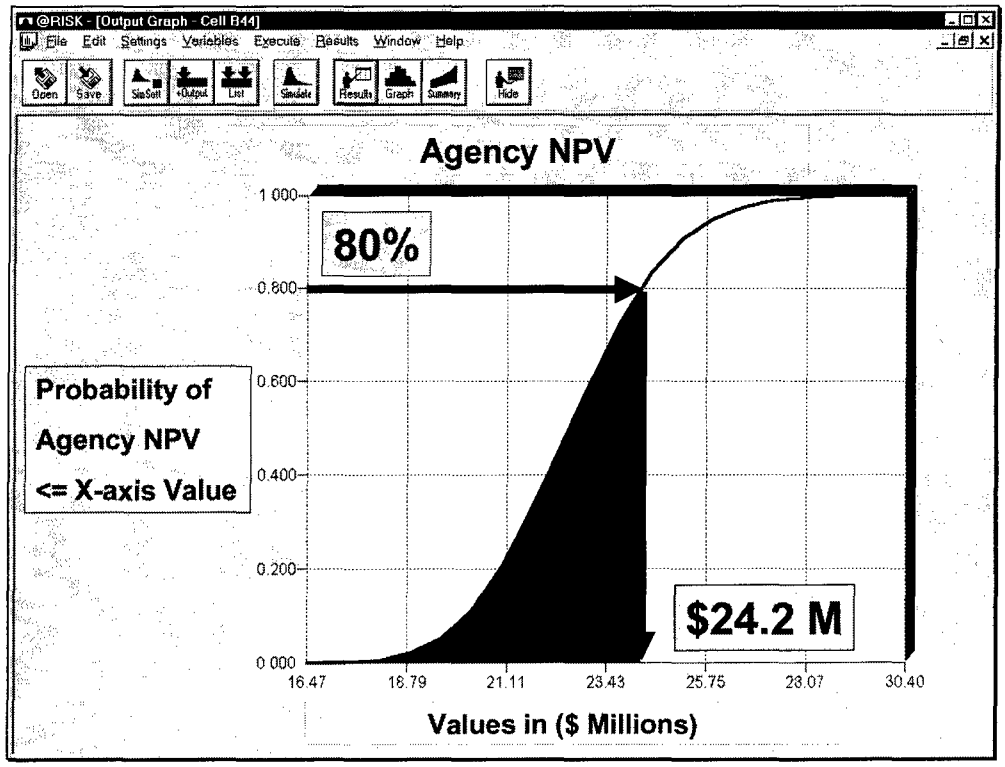
**47**



48


@RISK - [Output Graph - Cell B44]
File Edit Settings Variables Execute Results Window Help
Agency NPV
0.144
0.115
0.086
0.058
0.029
0.000
Relative Frequency, %
16.47
18.79
21.11
Agency NPV ($ Millions)
Graph Settings
Type Scaling Patterns Customize Variables to Graph
Type
Cumulative ascending
Display Using
Bar graph
Fitted curve
#Classes/
20
Use As Default
OK
Cancel

49

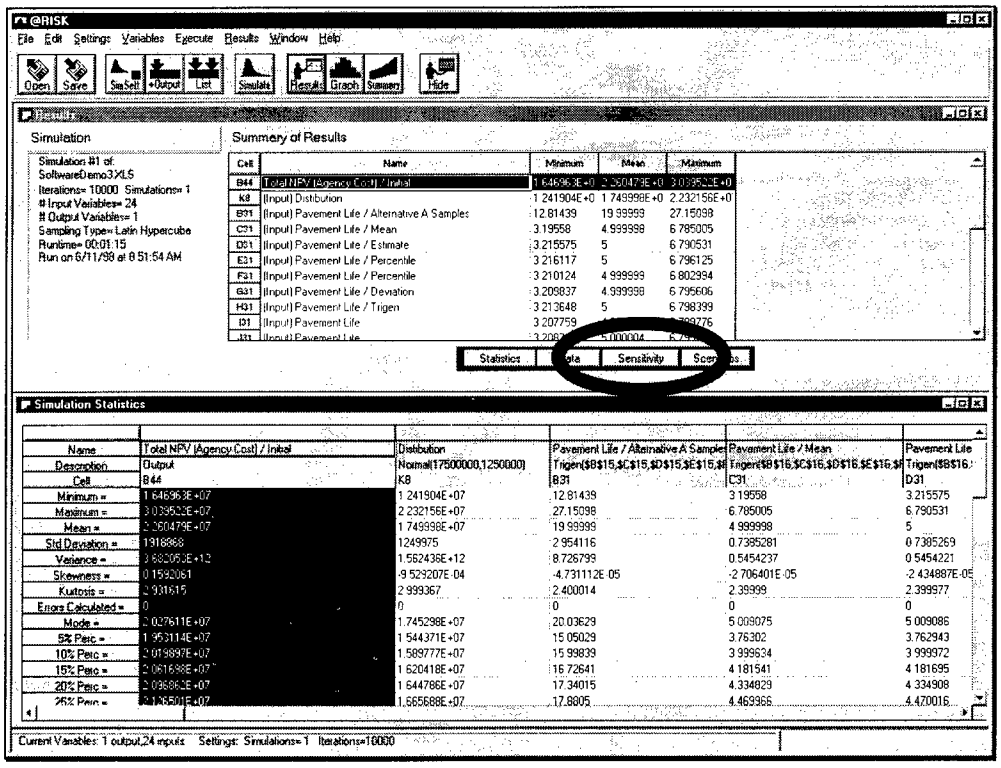

@RISK - [Output Graph - Cell B44]
File Edit Settings Variables Execute Results Window Help
Agency NPV
1.000
0.800
0.600
0.400
0.200
0.000
80%
Probability of
Agency NPV
<= X-axis Value
$24.2 M
16.47
18.79
21.11
23.43
25.75
28.07
30.40
Values in ($ Millions)

50

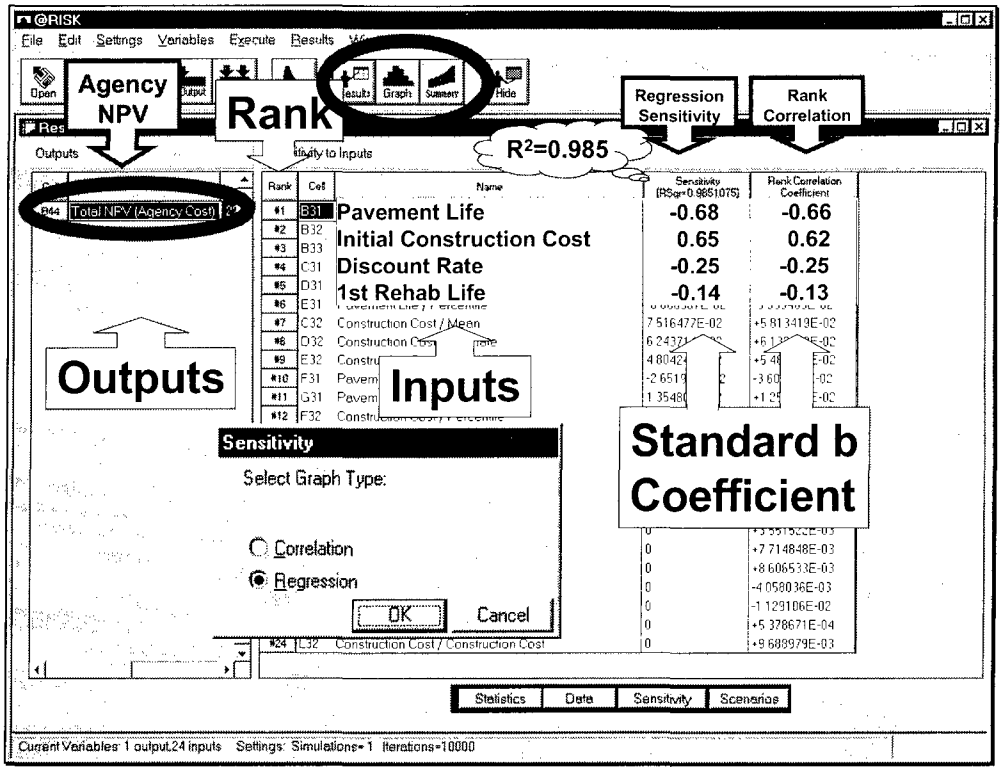
## Agency Cost

- Probability
- Sensitivity

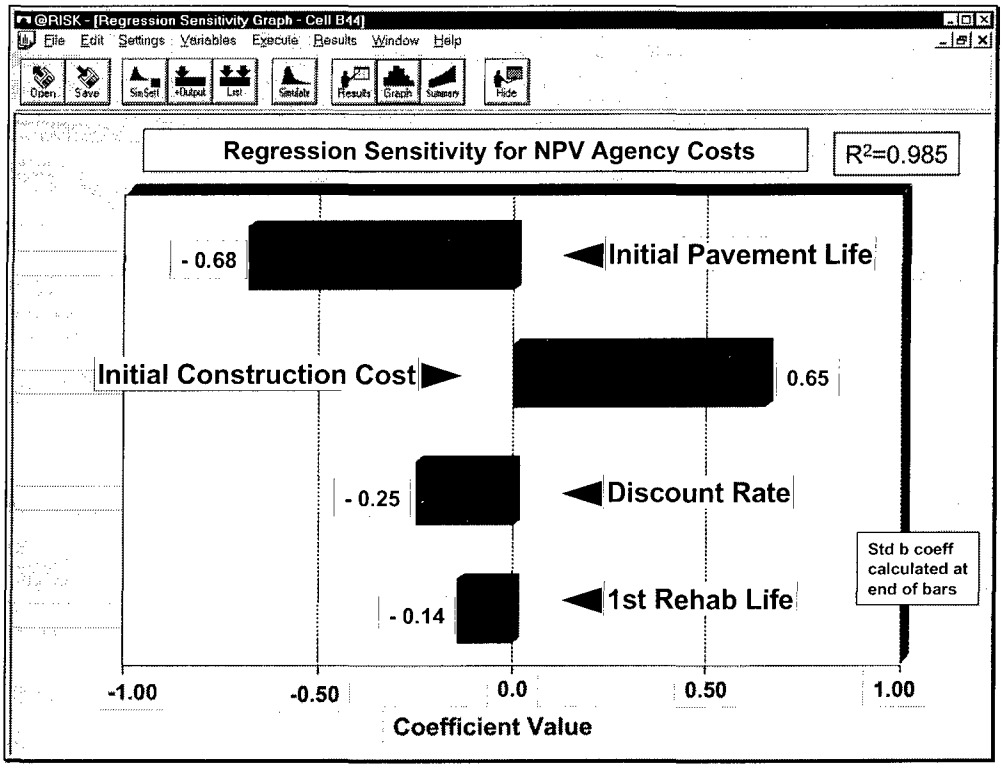
51



52


@RISK
Agency NPV
Rank
Regression Sensitivity
Rank Correlation
R²=0.985
Outputs
Inputs
Standard b Coefficient
Total NPV (Agency Cost)
Pavement Life
Initial Construction Cost
Discount Rate
1st Rehab Life
-0.68
-0.66
0.65
0.62
-0.25
-0.25
-0.14
-0.13
Sensitivity
Select Graph Type:
Correlation
Regression
OK
Cancel
Statistics
Data
Sensitivity
Scenarios
Current Variables: 1 output,24 inputs Settings: Simulations=1 Iterations=10000

53


@RISK - [Regression Sensitivity Graph - Cell B44]
Regression Sensitivity for NPV Agency Costs
R²=0.985
- 0.68
Initial Pavement Life
Initial Construction Cost
0.65
- 0.25
Discount Rate
- 0.14
1st Rehab Life
Std b coeff calculated at end of bars
-1.00
-0.50
0.0
0.50
1.00
Coefficient Value

54

## Sensitivity Analysis Observations

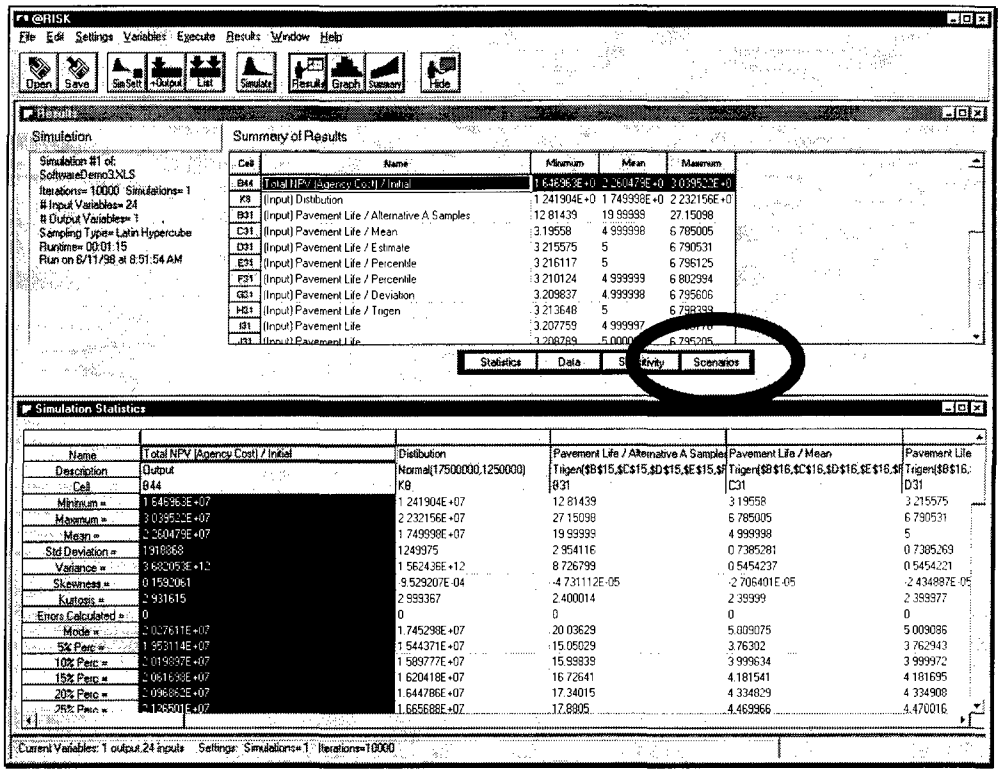
- Initial Pavement Life and Initial Construction Cost have the greatest influence on Agency NPV
- Discount Rate and 1st Rehab life have minor influence on Agency NPV

55

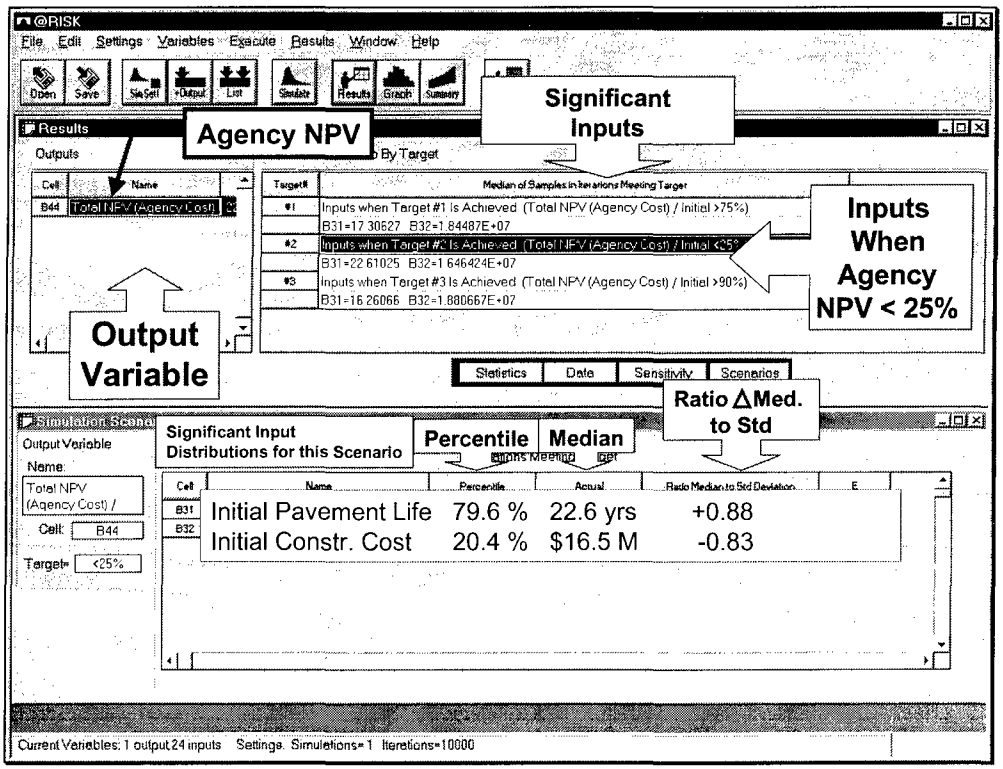
## Agency Cost

- Probability
- Sensitivity
- Scenario Analysis

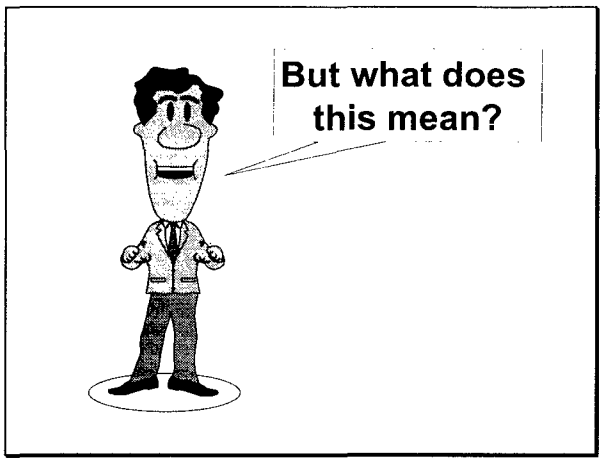
56


@RISK
File Edit Settings Variables Execute Results Window Help
Results
Simulation
Summary of Results
Statistics
Data
Scenarios
Simulation Statistics

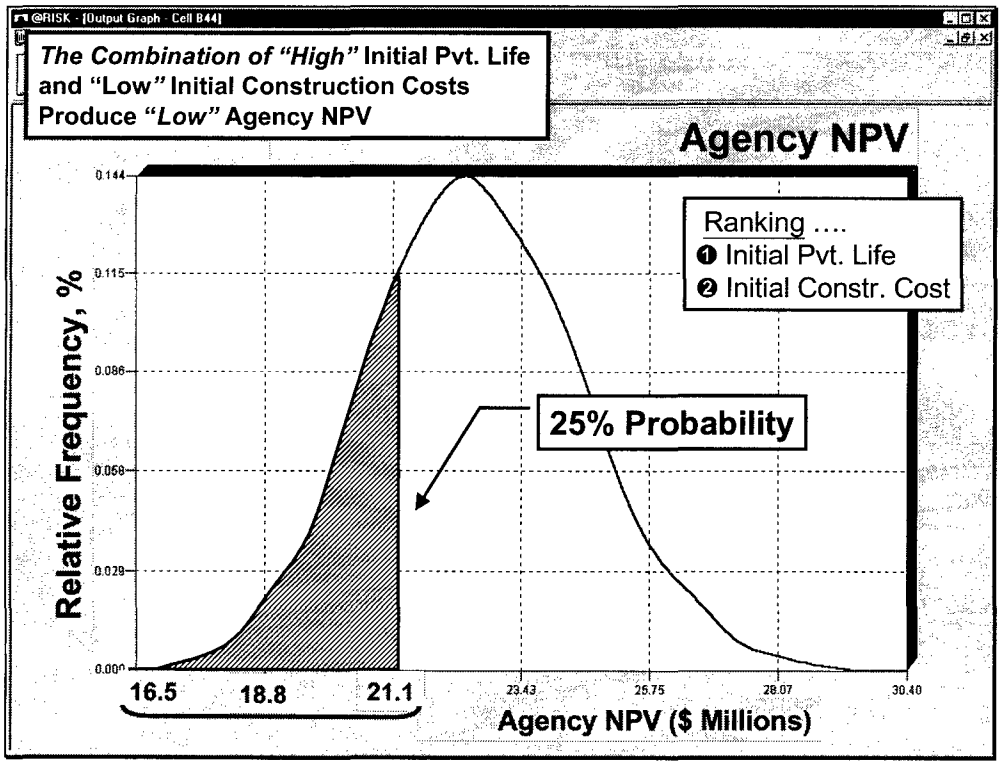
57


@RISK
Agency NPV
Significant Inputs
Inputs When Agency NPV < 25%
Output Variable
Ratio ΔMed. to Std
Significant Input Distributions for this Scenario
Percentile
Median
Initial Pavement Life 79.6 % 22.6 yrs +0.88
Initial Constr. Cost 20.4 % $16.5 M -0.83

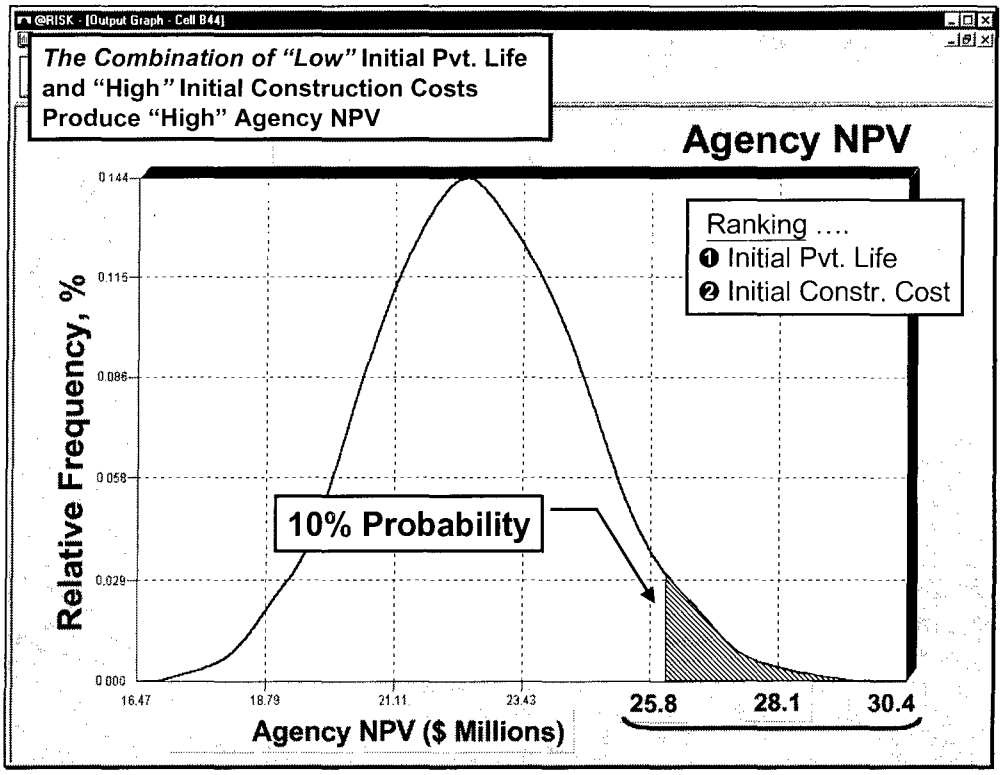
58


But what does this mean?

59


@RISK - [Output Graph - Cell B44]
The Combination of "High" Initial Pvt. Life and "Low" Initial Construction Costs Produce "Low" Agency NPV
Agency NPV
Ranking ....
❶ Initial Pvt. Life
❷ Initial Constr. Cost
25% Probability
Relative Frequency, %
0.144
0.115
0.086
0.058
0.029
0.000
16.5
18.8
21.1
23.43
25.75
28.07
30.40
Agency NPV ($ Millions)

60




61

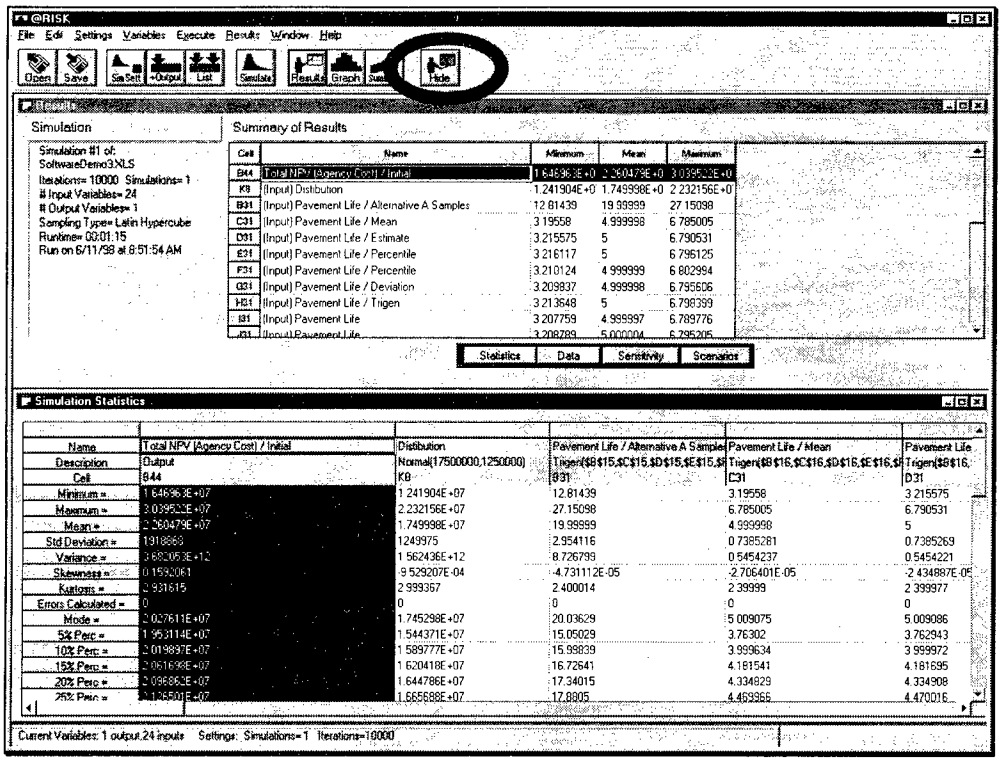
## Scenario Analysis Observations

***The Combination of ....***

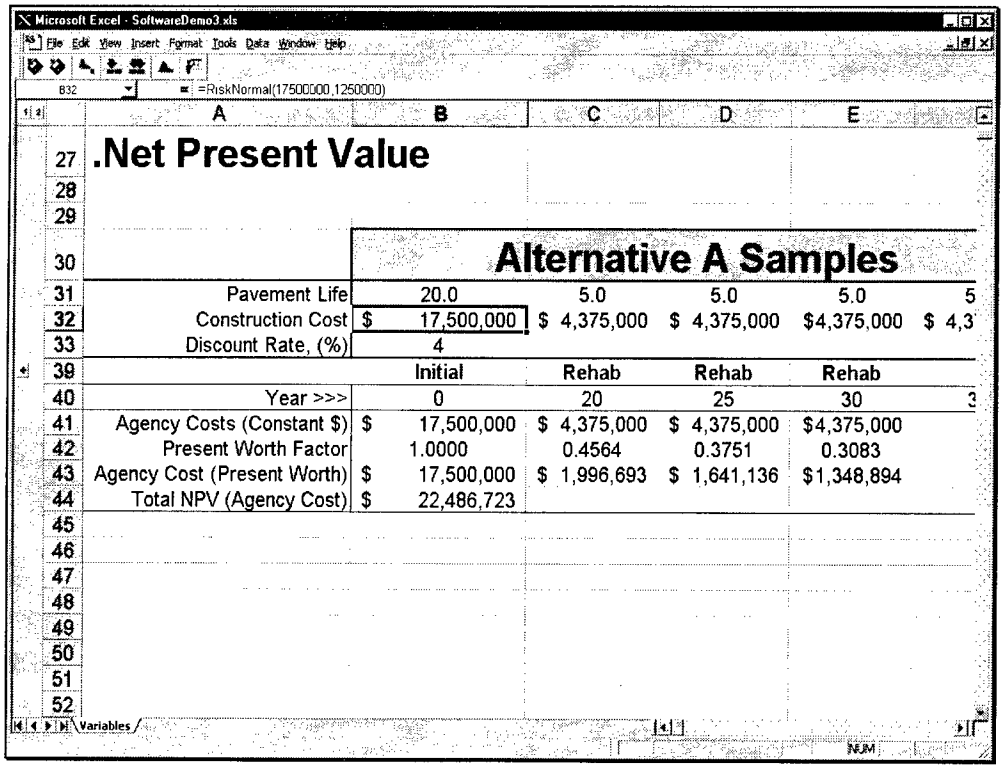
- *"High"* Initial Pvt. Life and *"Low"* Initial Construction Costs Produce *"Low"* [< 25%] Agency NPV

- *"Low"* Initial Pvt. Life and *"High"* Initial Construction Costs Produce *"High"* [>90%] Agency NPV

**62**


@RISK
File Edit Settings Variables Execute Results Window Help
Open Save Hide
Results
Simulation
Simulation #1 of: SoftwareDemo3.XLS
Iterations= 10000 Simulations= 1
# Input Variables= 24
# Output Variables= 1
Sampling Type= Latin Hypercube
Runtime= 00:01:15
Run on 6/11/99 at 8:51:54 AM
Summary of Results
Cell Name Minimum Mean Maximum
B44 Total NPV (Agency Cost) / Initial 1.646963E+07 2.260479E+07 3.039532E+07
K8 (Input) Distribution 1.241904E+07 1.749998E+07 2.232156E+07
B31 (Input) Pavement Life / Alternative A Samples 12.81439 19.99999 27.15098
C31 (Input) Pavement Life / Mean 3.19558 4.999998 6.785005
D31 (Input) Pavement Life / Estimate 3.215575 5 6.790531
E31 (Input) Pavement Life / Percentile 3.216117 5 6.795125
F31 (Input) Pavement Life / Percentile 3.210124 4.999999 6.802994
G31 (Input) Pavement Life / Deviation 3.209837 4.999998 6.795606
H31 (Input) Pavement Life / Trigen 3.213648 5 6.798399
I31 (Input) Pavement Life 3.207759 4.999997 6.789776
J31 (Input) Pavement Life 3.208289 5.000004 6.795205
Statistics Data Sensitivity Scenarios
Simulation Statistics
Name | Total NPV (Agency Cost) / Initial | Distribution | Pavement Life / Alternative A Samples | Pavement Life / Mean | Pavement Life
Description | Output | Normal(17500000,1250000) | Trigen($B$15,$C$15,$D$15,$E$15,$F | Trigen($B$16,$C$16,$D$16,$E$16,$F | Trigen($B$16,
Cell | B44 | K8 | B31 | C31 | D31
Minimum = | 1.646963E+07 | 1.241904E+07 | 12.81439 | 3.19558 | 3.215575
Maximum = | 3.039532E+07 | 2.232156E+07 | 27.15098 | 6.785005 | 6.790531
Mean = | 2.260479E+07 | 1.749998E+07 | 19.99999 | 4.999998 | 5
Std Deviation = | 1918868 | 1249975 | 2.954116 | 0.7385281 | 0.7385269
Variance = | 3.682053E+12 | 1.562436E+12 | 8.726799 | 0.5454237 | 0.5454221
Skewness = | 0.1592061 | -9.529207E-04 | -4.731112E-05 | -2.706401E-05 | -2.434887E-05
Kurtosis = | 2.931615 | 2.999367 | 2.400014 | 2.39999 | 2.399977
Errors Calculated = | 0 | 0 | 0 | 0 | 0
Mode = | 2.027611E+07 | 1.745298E+07 | 20.03629 | 5.009075 | 5.009086
5% Perc = | 1.953114E+07 | 1.544371E+07 | 15.05029 | 3.76302 | 3.762943
10% Perc = | 2.019897E+07 | 1.589777E+07 | 15.99839 | 3.999634 | 3.999972
15% Perc = | 2.061698E+07 | 1.620418E+07 | 16.72641 | 4.181541 | 4.181695
20% Perc = | 2.096862E+07 | 1.644786E+07 | 17.34015 | 4.334829 | 4.334908
25% Perc = | 2.126501E+07 | 1.665688E+07 | 17.8805 | 4.469366 | 4.470016
Current Variables: 1 output,24 inputs Settings: Simulations=1 Iterations=10000

**63**


Microsoft Excel - SoftwareDemo3.xls
File Edit View Insert Format Tools Data Window Help
B32 =RiskNormal(17500000,1250000)
A B C D E
27 .Net Present Value
30 Alternative A Samples
31 Pavement Life 20.0 5.0 5.0 5.0 5
32 Construction Cost $ 17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000 $ 4,3
33 Discount Rate, (%) 4
39 Initial Rehab Rehab Rehab
40 Year >>> 0 20 25 30 3
41 Agency Costs (Constant $) $ 17,500,000 $ 4,375,000 $ 4,375,000 $4,375,000
42 Present Worth Factor 1.0000 0.4564 0.3751 0.3083
43 Agency Cost (Present Worth) $ 17,500,000 $ 1,996,693 $ 1,641,136 $1,348,894
44 Total NPV (Agency Cost) $ 22,486,723
Variables
NUM

64

## Risk Modeling Review

- Build the traditional NPV model
- Identify and describe uncertain variables using risk functions
- Define simulation parameters and output variables
- Run the simulation
- Analyze Results

65

## Parting Caveat ...

- *@Risk* and *BestFit* have been used for illustration purposes.
- Other software packages are available to do risk analysis.

66

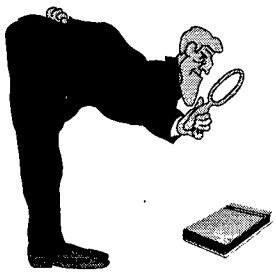
## For More Information:

- @Risk and BestFit
  - Palisade Corporation
    http://www.palisade.com
    Phone: 800-432-7475
- Crystal Ball
  - Decisioneering
    http://www.decisioneering.com
    Phone: 800-289-2550

67

End Session

1



# LCCA

## Class Exercise Revisited

2

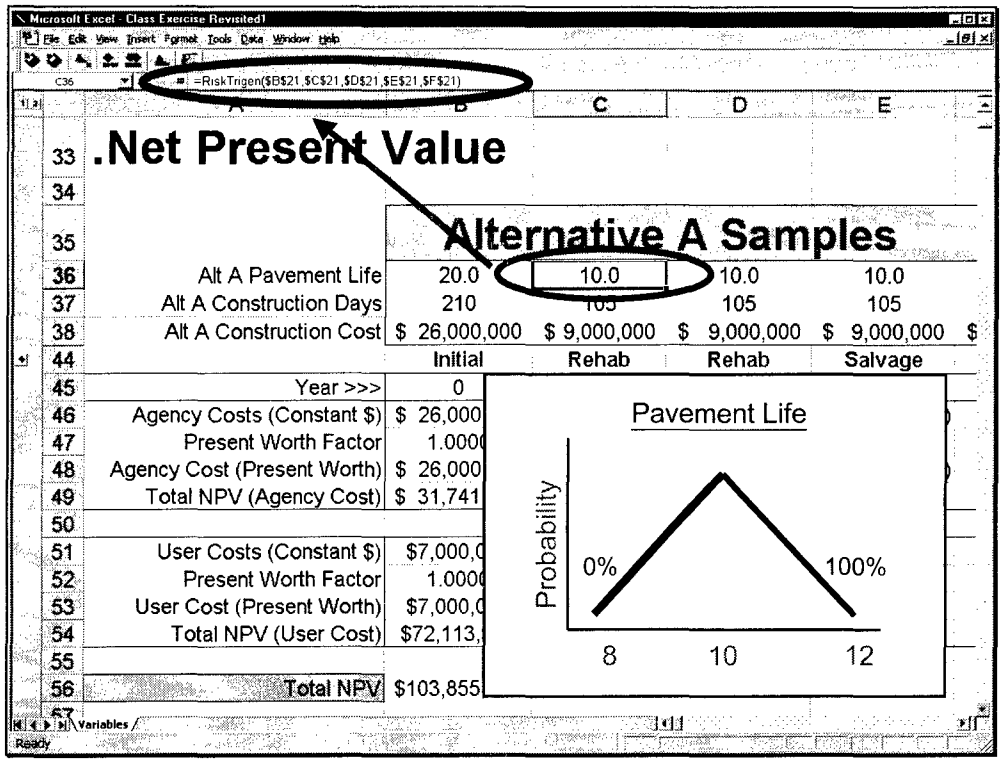
Microsoft Excel - Class Exercise Revisited1.xls

# Class Exercise Revisited

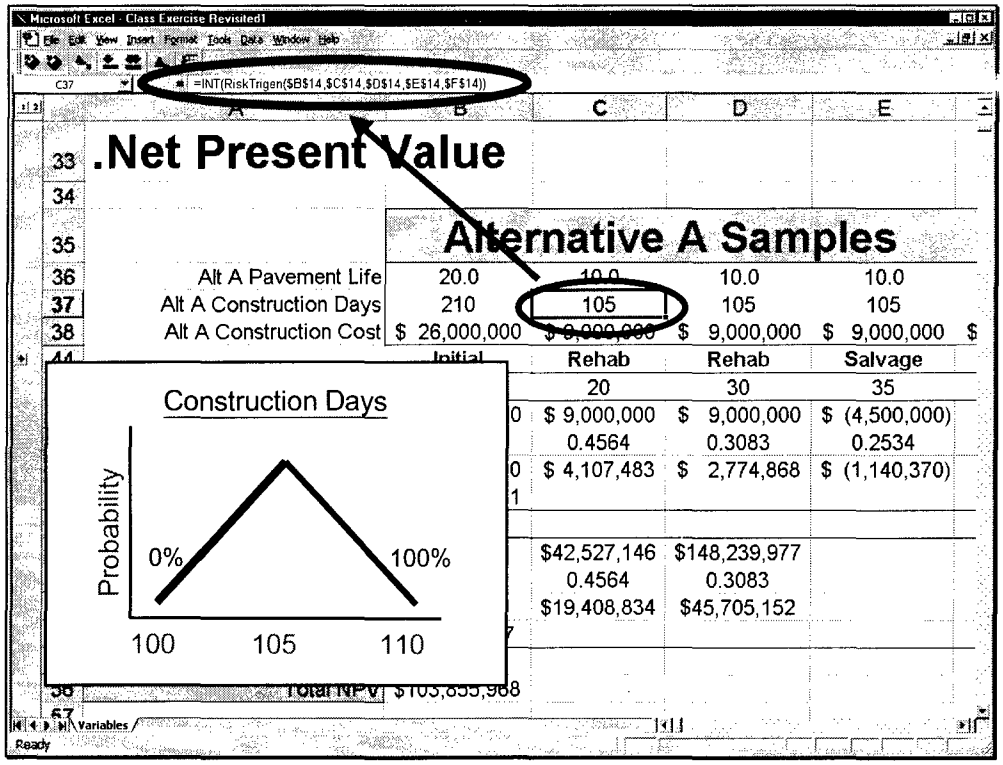
| | | |
|---|---|---|
| Analysis Period | 35 | years |
| Discount Rate | 4.0% | |

| | .Risk Analysis Input Parameters | | | | | |
|---|---|---|---|---|---|---|
| Variable | Lower Estimate | Most Likely | Upper Estimate | Lower Percentile | Upper Percentile | Distibution Type |
| **Construction Days** | | | | | | |
| **Alternative A** | | | | | | |
| Initial | 200 | 210 | 220 | 0 | 100 | Trigen |
| Rehab | 100 | 105 | 110 | 0 | 100 | Trigen |
| **Alternative B** | | | | | | |
| Initial | 150 | 165 | 180 | 0 | 100 | Trigen |
| Rehab | 70 | 85 | 100 | 0 | 100 | Trigen |
| **Performance Estimates** | | | | | | |
| **Alternative A** | | | | | | |
| Initial | 16 | 20 | 24 | 0.00 | 100.00 | Trigen |
| Rehab | 8 | 10 | 12 | 0.00 | 100.00 | Trigen |
| **Alternative B** | | | | | | |
| Initial | 10 | 13 | 16 | 0.00 | 100.00 | Trigen |
| Rehab | 6 | 7 | 8 | 0.00 | 100.00 | Trigen |

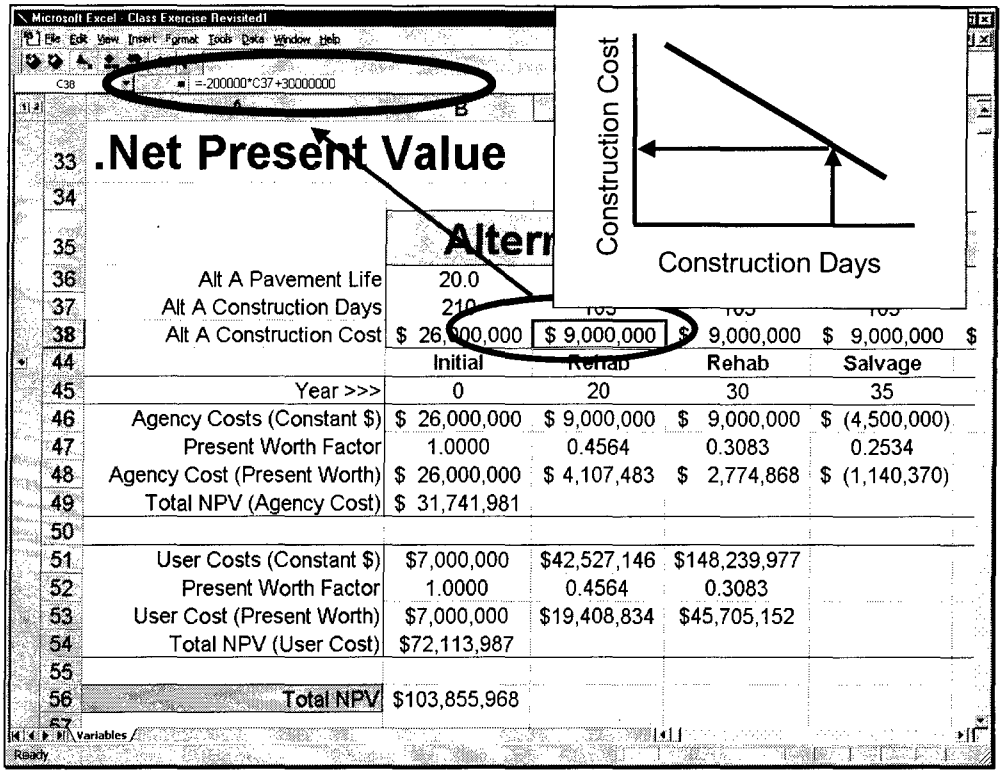
3


Microsoft Excel - Class Exercise Revisited1
=RiskTrigen($B$21,$C$21,$D$21,$E$21,$F$21)
.Net Present Value
Alternative A Samples
Alt A Pavement Life 20.0 10.0 10.0 10.0
Alt A Construction Days 210 105 105 105
Alt A Construction Cost $ 26,000,000 $ 9,000,000 $ 9,000,000 $ 9,000,000
Initial Rehab Rehab Salvage
Year >>> 0
Agency Costs (Constant $) $ 26,000
Present Worth Factor 1.000
Agency Cost (Present Worth) $ 26,000
Total NPV (Agency Cost) $ 31,741
User Costs (Constant $) $7,000,
Present Worth Factor 1.000
User Cost (Present Worth) $7,000,
Total NPV (User Cost) $72,113,
Total NPV $103,855
Pavement Life
Probability
0%
100%
8
10
12
Variables
Ready

4


Microsoft Excel - Class Exercise Revisited1
=INT(RiskTrigen($B$14,$C$14,$D$14,$E$14,$F$14))
.Net Present Value
Alternative A Samples
Alt A Pavement Life 20.0 10.0 10.0 10.0
Alt A Construction Days 210 105 105 105
Alt A Construction Cost $ 26,000,000 $ 9,000,000 $ 9,000,000 $
Initial Rehab Rehab Salvage
20 30 35
$ 9,000,000 $ 9,000,000 $ (4,500,000)
0.4564 0.3083 0.2534
$ 4,107,483 $ 2,774,868 $ (1,140,370)
$42,527,146 $148,239,977
0.4564 0.3083
$19,408,834 $45,705,152
Construction Days
Probability
0%
100%
100
105
110
Variables
Ready

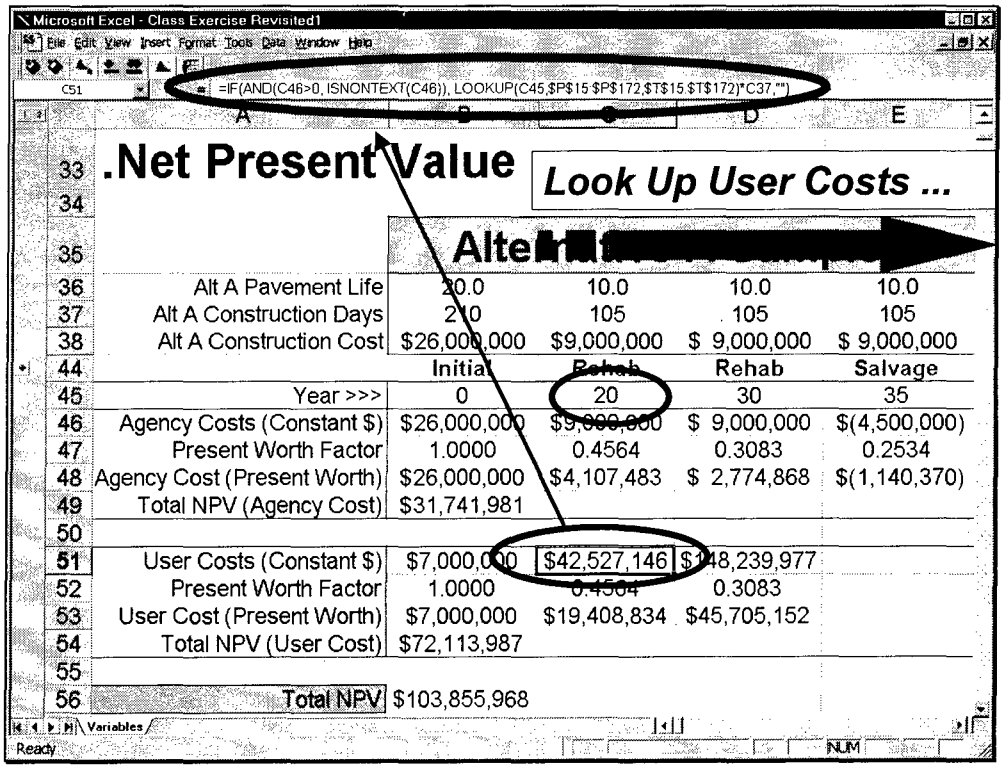
5




.Net Present Value

| | | Alter | | | |
|---|---|---|---|---|---|
| Alt A Pavement Life | | 20.0 | | | |
| Alt A Construction Days | | 210 | | | |
| Alt A Construction Cost | | $ 26,000,000 | $ 9,000,000 | $ 9,000,000 | $ 9,000,000 |
| | | Initial | Rehab | Rehab | Salvage |
| Year >>> | | 0 | 20 | 30 | 35 |
| Agency Costs (Constant $) | | $ 26,000,000 | $ 9,000,000 | $ 9,000,000 | $ (4,500,000) |
| Present Worth Factor | | 1.0000 | 0.4564 | 0.3083 | 0.2534 |
| Agency Cost (Present Worth) | | $ 26,000,000 | $ 4,107,483 | $ 2,774,868 | $ (1,140,370) |
| Total NPV (Agency Cost) | | $ 31,741,981 | | | |
| User Costs (Constant $) | | $7,000,000 | $42,527,146 | $148,239,977 | |
| Present Worth Factor | | 1.0000 | 0.4564 | 0.3083 | |
| User Cost (Present Worth) | | $7,000,000 | $19,408,834 | $45,705,152 | |
| Total NPV (User Cost) | | $72,113,987 | | | |
| | Total NPV | $103,855,968 | | | |

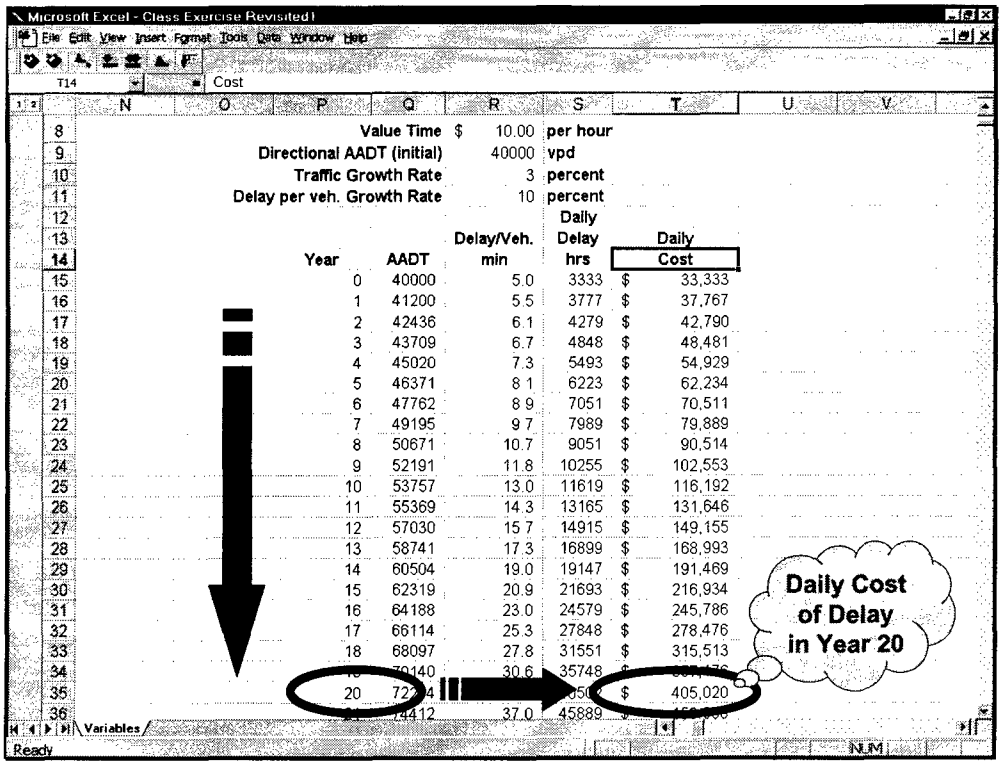
6



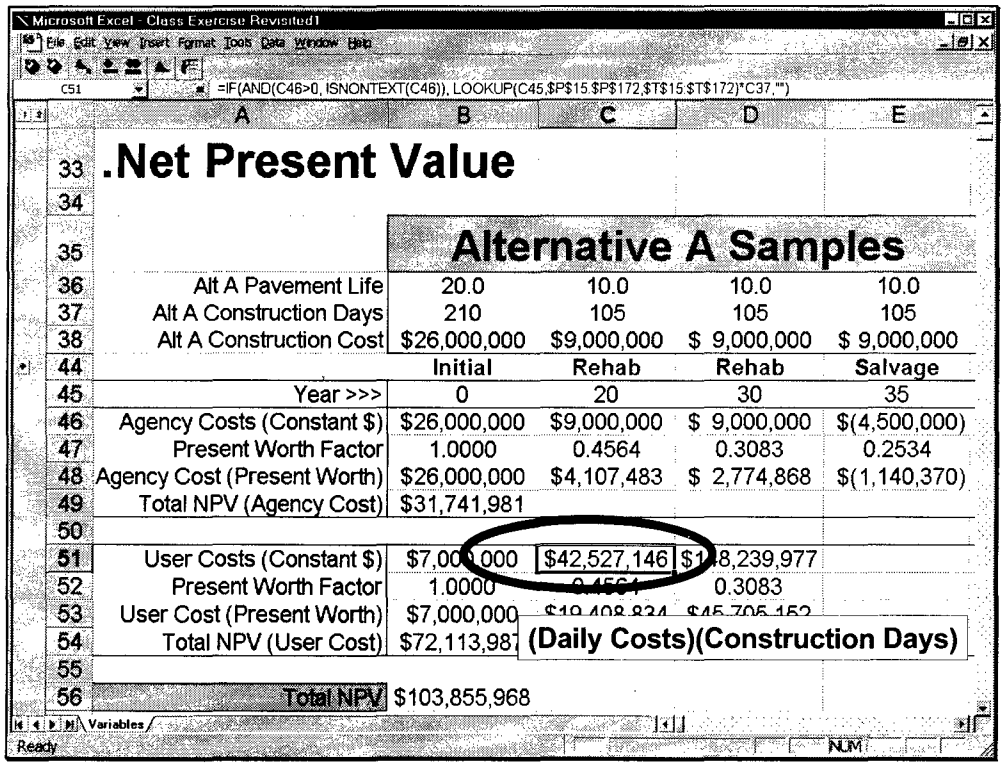

.Net Present Value *Look Up User Costs ...*

| | | Alte | | | |
|---|---|---|---|---|---|
| Alt A Pavement Life | | 20.0 | 10.0 | 10.0 | 10.0 |
| Alt A Construction Days | | 210 | 105 | 105 | 105 |
| Alt A Construction Cost | | $26,000,000 | $9,000,000 | $ 9,000,000 | $ 9,000,000 |
| | | Initial | Rehab | Rehab | Salvage |
| Year >>> | | 0 | 20 | 30 | 35 |
| Agency Costs (Constant $) | | $26,000,000 | $9,000,000 | $ 9,000,000 | $(4,500,000) |
| Present Worth Factor | | 1.0000 | 0.4564 | 0.3083 | 0.2534 |
| Agency Cost (Present Worth) | | $26,000,000 | $4,107,483 | $ 2,774,868 | $(1,140,370) |
| Total NPV (Agency Cost) | | $31,741,981 | | | |
| User Costs (Constant $) | | $7,000,000 | $42,527,146 | $148,239,977 | |
| Present Worth Factor | | 1.0000 | 0.4564 | 0.3083 | |
| User Cost (Present Worth) | | $7,000,000 | $19,408,834 | $45,705,152 | |
| Total NPV (User Cost) | | $72,113,987 | | | |
| | Total NPV | $103,855,968 | | | |

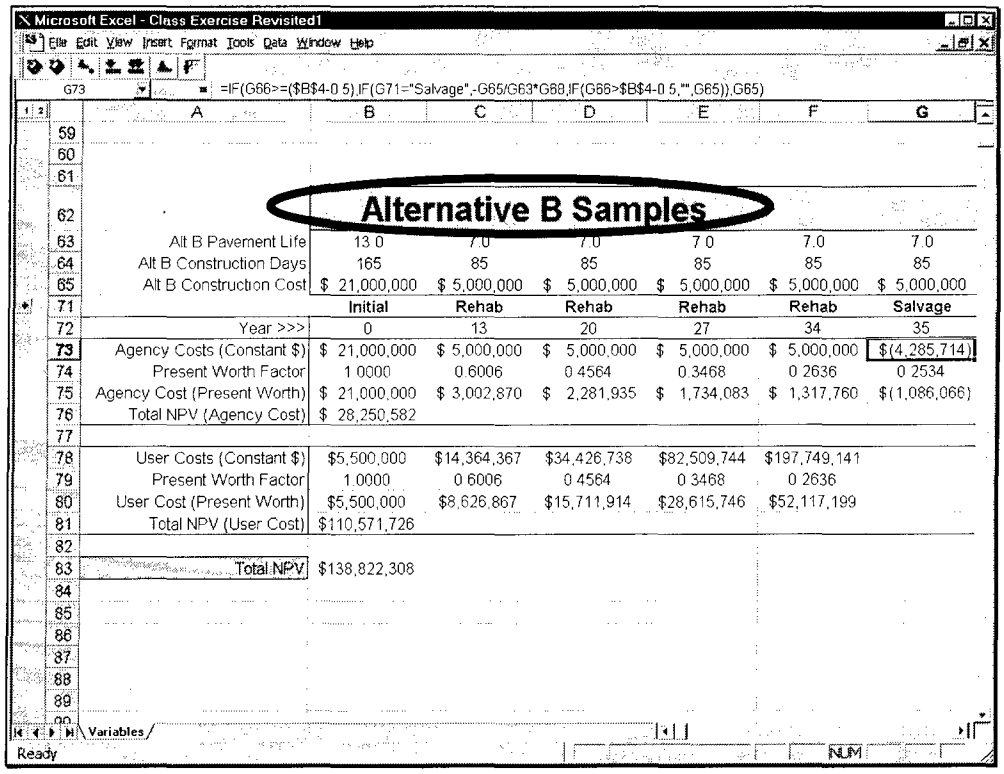
**7**


Microsoft Excel - Class Exercise Revisited1
Cost
Value Time $ 10.00 per hour
Directional AADT (initial) 40000 vpd
Traffic Growth Rate 3 percent
Delay per veh. Growth Rate 10 percent
Year AADT Delay/Veh. min Daily Delay hrs Daily Cost
0 40000 5.0 3333 $ 33,333
1 41200 5.5 3777 $ 37,767
2 42436 6.1 4279 $ 42,790
3 43709 6.7 4848 $ 48,481
4 45020 7.3 5493 $ 54,929
5 46371 8.1 6223 $ 62,234
6 47762 8.9 7051 $ 70,511
7 49195 9.7 7989 $ 79,889
8 50671 10.7 9051 $ 90,514
9 52191 11.8 10255 $ 102,553
10 53757 13.0 11619 $ 116,192
11 55369 14.3 13165 $ 131,646
12 57030 15.7 14915 $ 149,155
13 58741 17.3 16899 $ 168,993
14 60504 19.0 19147 $ 191,469
15 62319 20.9 21693 $ 216,934
16 64188 23.0 24579 $ 245,786
17 66114 25.3 27848 $ 278,476
18 68097 27.8 31551 $ 315,513
20 $ 405,020
37.0 45889
Daily Cost of Delay in Year 20
Variables
Ready
NUM

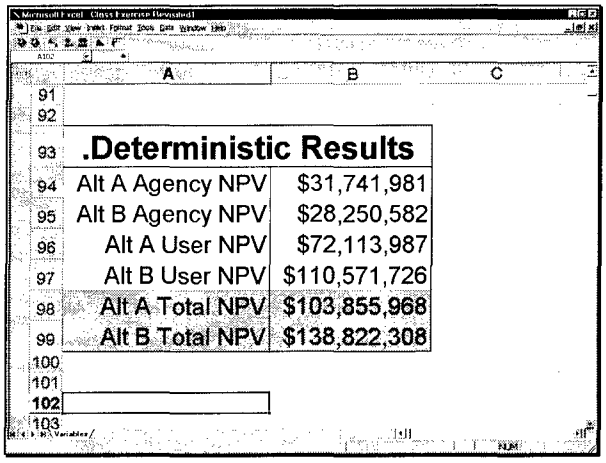
**8**


Microsoft Excel - Class Exercise Revisited1
=IF(AND(C46>0, ISNONTEXT(C46)), LOOKUP(C45,$P$15:$P$172,$T$15:$T$172)*C37,"")
.Net Present Value
Alternative A Samples
Alt A Pavement Life 20.0 10.0 10.0 10.0
Alt A Construction Days 210 105 105 105
Alt A Construction Cost $26,000,000 $9,000,000 $ 9,000,000 $ 9,000,000
Initial Rehab Rehab Salvage
Year >>> 0 20 30 35
Agency Costs (Constant $) $26,000,000 $9,000,000 $ 9,000,000 $(4,500,000)
Present Worth Factor 1.0000 0.4564 0.3083 0.2534
Agency Cost (Present Worth) $26,000,000 $4,107,483 $ 2,774,868 $(1,140,370)
Total NPV (Agency Cost) $31,741,981
User Costs (Constant $) $7,000,000 $42,527,146 $48,239,977
Present Worth Factor 1.0000 0.4564 0.3083
User Cost (Present Worth) $7,000,000
Total NPV (User Cost) $72,113,98
(Daily Costs)(Construction Days)
Total NPV $103,855,968
Variables
Ready
NUM

9


Microsoft Excel - Class Exercise Revisited1
File Edit View Insert Format Tools Data Window Help
G73
=IF(G66>=($B$4-0 5),IF(G71="Salvage",-G65/G63*G68,IF(G66>$B$4-0 5,"",G65)),G65)
Alternative B Samples
Alt B Pavement Life 13 0 7.0 7.0 7 0 7.0 7.0
Alt B Construction Days 165 85 85 85 85 85
Alt B Construction Cost $ 21,000,000 $ 5,000,000 $ 5,000,000 $ 5,000,000 $ 5,000,000 $ 5,000,000
Initial Rehab Rehab Rehab Rehab Salvage
Year >>> 0 13 20 27 34 35
Agency Costs (Constant $) $ 21,000,000 $ 5,000,000 $ 5,000,000 $ 5,000,000 $ 5,000,000 $(4,285,714)
Present Worth Factor 1 0000 0.6006 0 4564 0.3468 0 2636 0 2534
Agency Cost (Present Worth) $ 21,000,000 $ 3,002,870 $ 2,281,935 $ 1,734,083 $ 1,317,760 $(1,086,066)
Total NPV (Agency Cost) $ 28,250,582
User Costs (Constant $) $5,500,000 $14,364,367 $34,426,738 $82,509,744 $197,749,141
Present Worth Factor 1.0000 0 6006 0 4564 0 3468 0 2636
User Cost (Present Worth) $5,500,000 $8,626,867 $15,711,914 $28,615,746 $52,117,199
Total NPV (User Cost) $110,571,726
Total NPV $138,822,308
Variables
Ready
NUM

10


.Deterministic Results
Alt A Agency NPV $31,741,981
Alt B Agency NPV $28,250,582
Alt A User NPV $72,113,987
Alt B User NPV $110,571,726
Alt A Total NPV $103,855,968
Alt B Total NPV $138,822,308

11

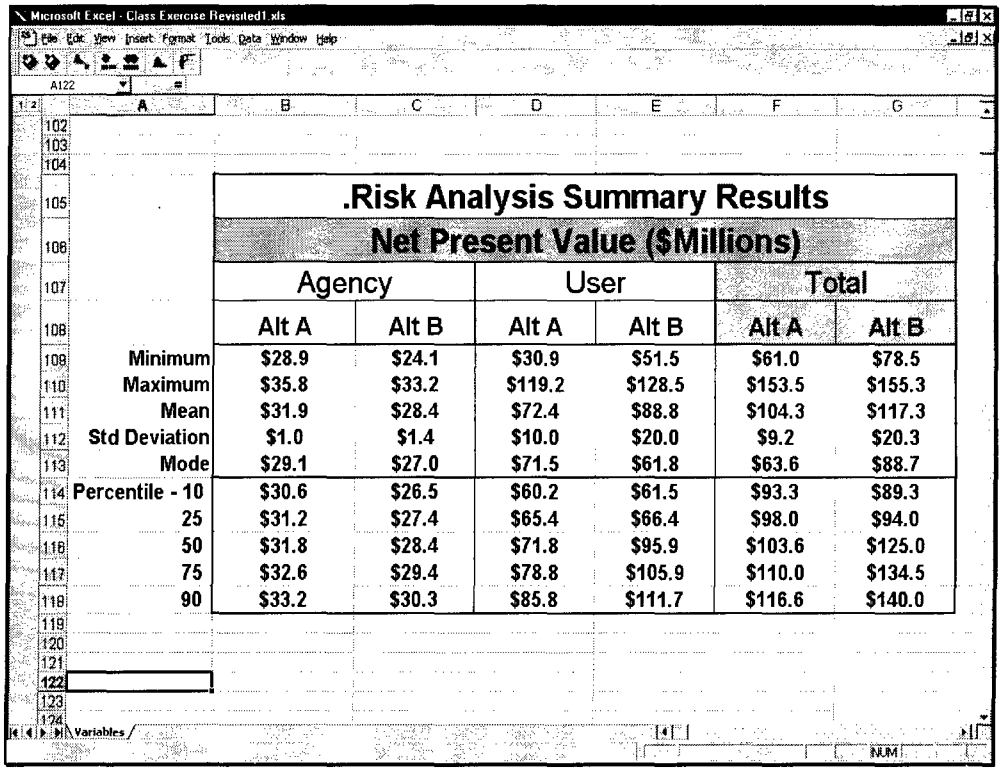
## Simulation Processing

- Latin Hypercube
- 44 Input Variables
- 6 Output Variables
- 10,000 Iterations
- Run Time = 3 min 51 sec

12

## Simulation Results

13




| .Risk Analysis Summary Results | | | | | | |
|---|---|---|---|---|---|---|
| Net Present Value ($Millions) | | | | | | |
| | Agency | | User | | Total | |
| | Alt A | Alt B | Alt A | Alt B | Alt A | Alt B |
| Minimum | $28.9 | $24.1 | $30.9 | $51.5 | $61.0 | $78.5 |
| Maximum | $35.8 | $33.2 | $119.2 | $128.5 | $153.5 | $155.3 |
| Mean | $31.9 | $28.4 | $72.4 | $88.8 | $104.3 | $117.3 |
| Std Deviation | $1.0 | $1.4 | $10.0 | $20.0 | $9.2 | $20.3 |
| Mode | $29.1 | $27.0 | $71.5 | $61.8 | $63.6 | $88.7 |
| Percentile - 10 | $30.6 | $26.5 | $60.2 | $61.5 | $93.3 | $89.3 |
| 25 | $31.2 | $27.4 | $65.4 | $66.4 | $98.0 | $94.0 |
| 50 | $31.8 | $28.4 | $71.8 | $95.9 | $103.6 | $125.0 |
| 75 | $32.6 | $29.4 | $78.8 | $105.9 | $110.0 | $134.5 |
| 90 | $33.2 | $30.3 | $85.8 | $111.7 | $116.6 | $140.0 |

14

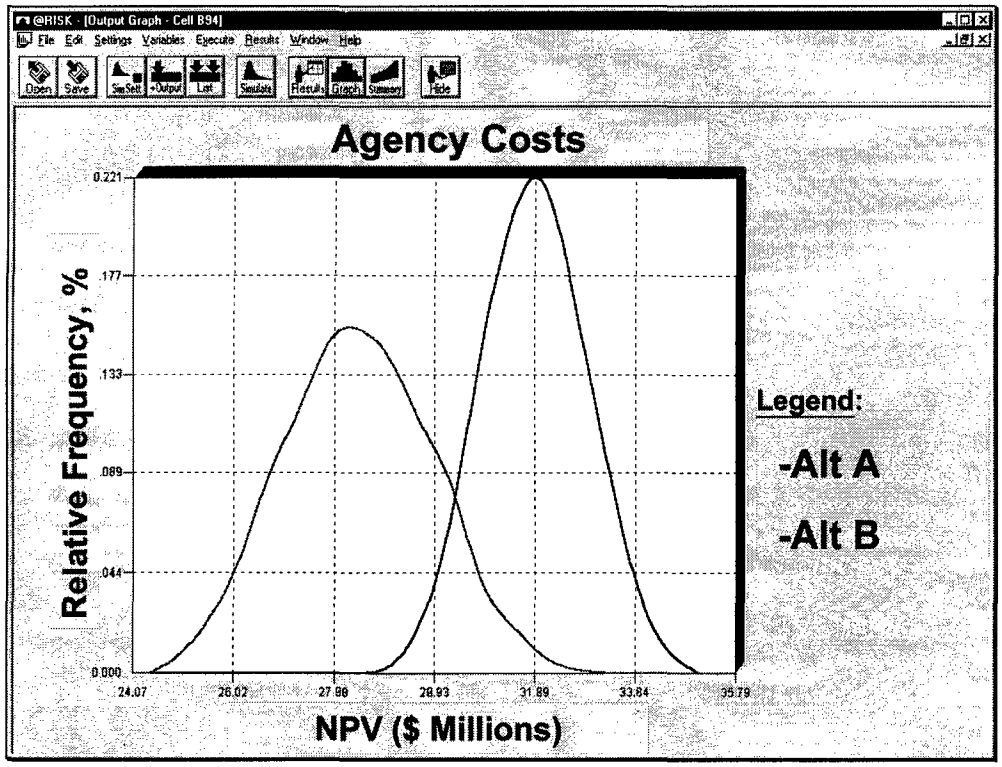
# Agency Costs

15

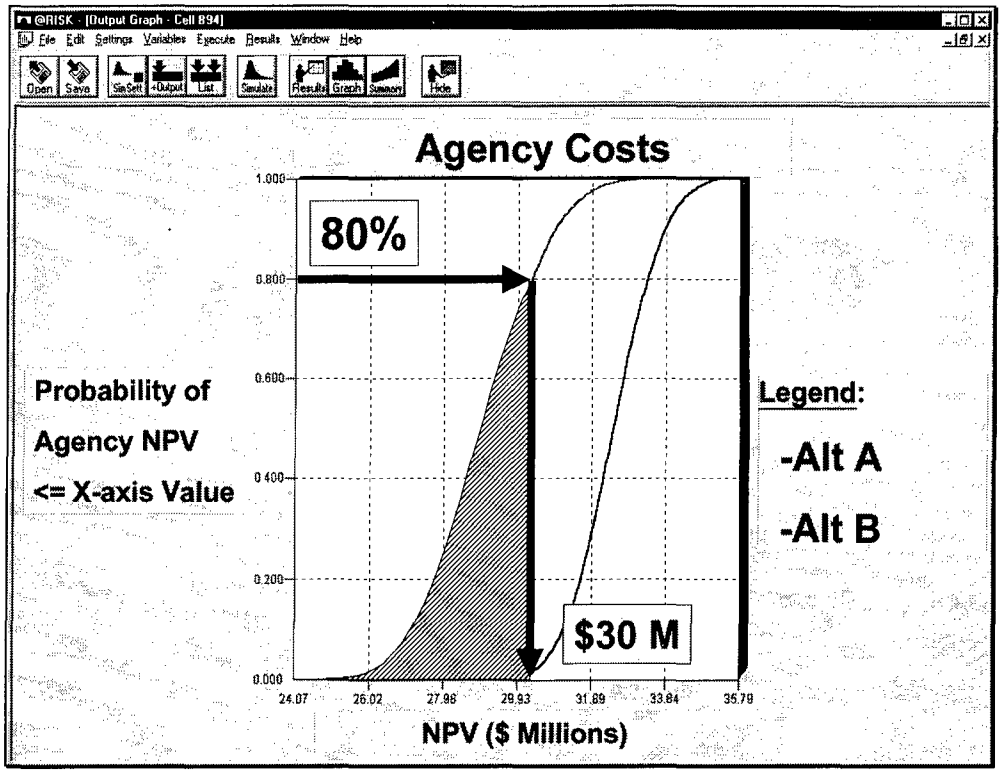
## Agency Cost

- Probability
- Sensitivity
- Scenario Analysis

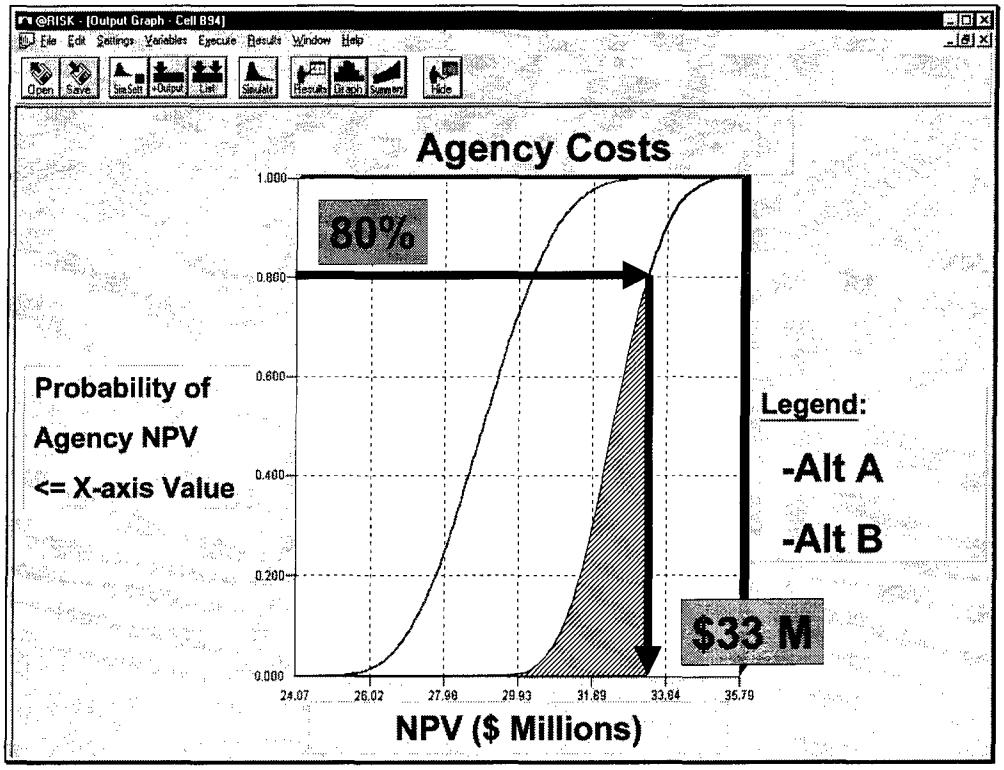
16



17


@RISK - [Output Graph - Cell B94]
File Edit Settings Variables Execute Results Window Help
Open Save SimSett +Output List Simulate Results Graph Summary Hide
Agency Costs
80%
$30 M
Probability of
Agency NPV
<= X-axis Value
Legend:
-Alt A
-Alt B
1.000
0.800
0.600
0.400
0.200
0.000
24.07
26.02
27.98
29.93
31.89
33.84
35.79
NPV ($ Millions)

18


@RISK - [Output Graph - Cell B94]
File Edit Settings Variables Execute Results Window Help
Open Save SimSett +Output List Simulate Results Graph Summary Hide
Agency Costs
80%
$33 M
Probability of
Agency NPV
<= X-axis Value
Legend:
-Alt A
-Alt B
1.000
0.800
0.600
0.400
0.200
0.000
24.07
26.02
27.98
29.93
31.89
33.84
35.79
NPV ($ Millions)

19

## Probability Observations

Agency Costs …

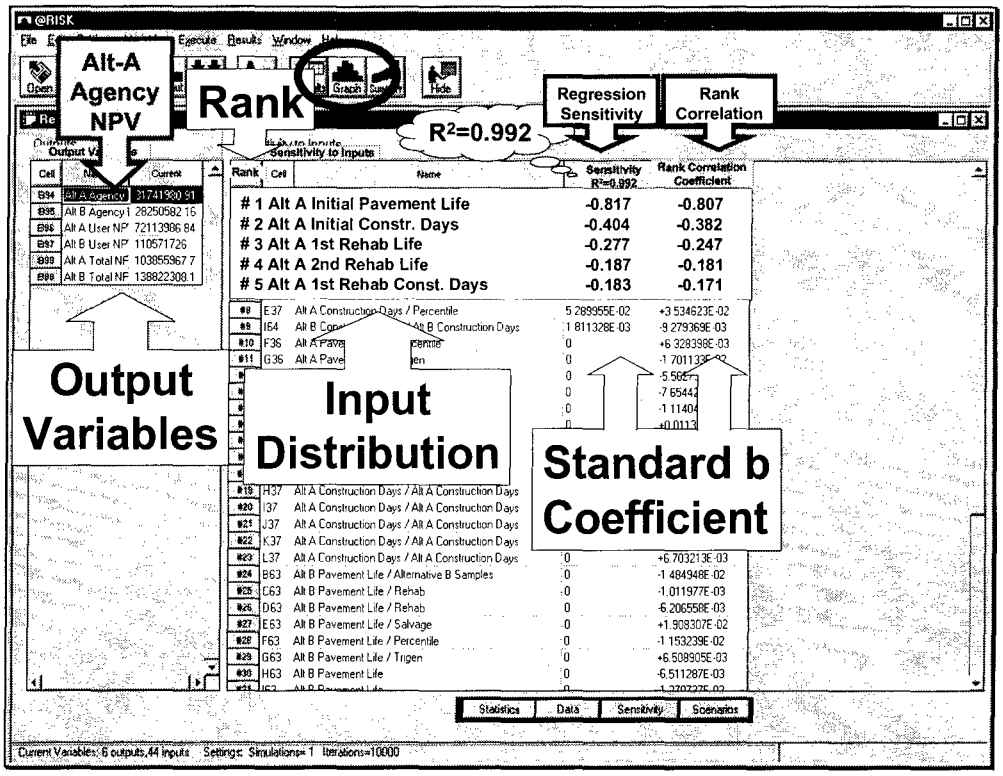
- Alt-B is 42% *more* variable than Alt-A
- At *any* given level of reliability Alt-B is *less* expensive than Alt-A.

20

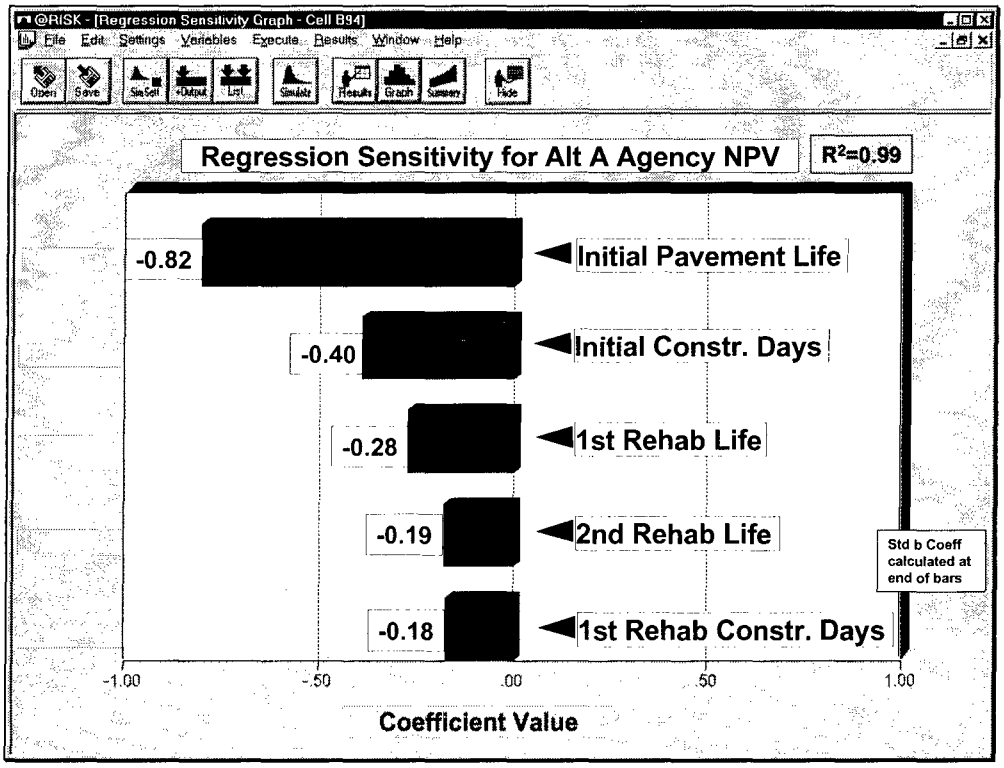
## Agency Cost

- Probability
- Sensitivity

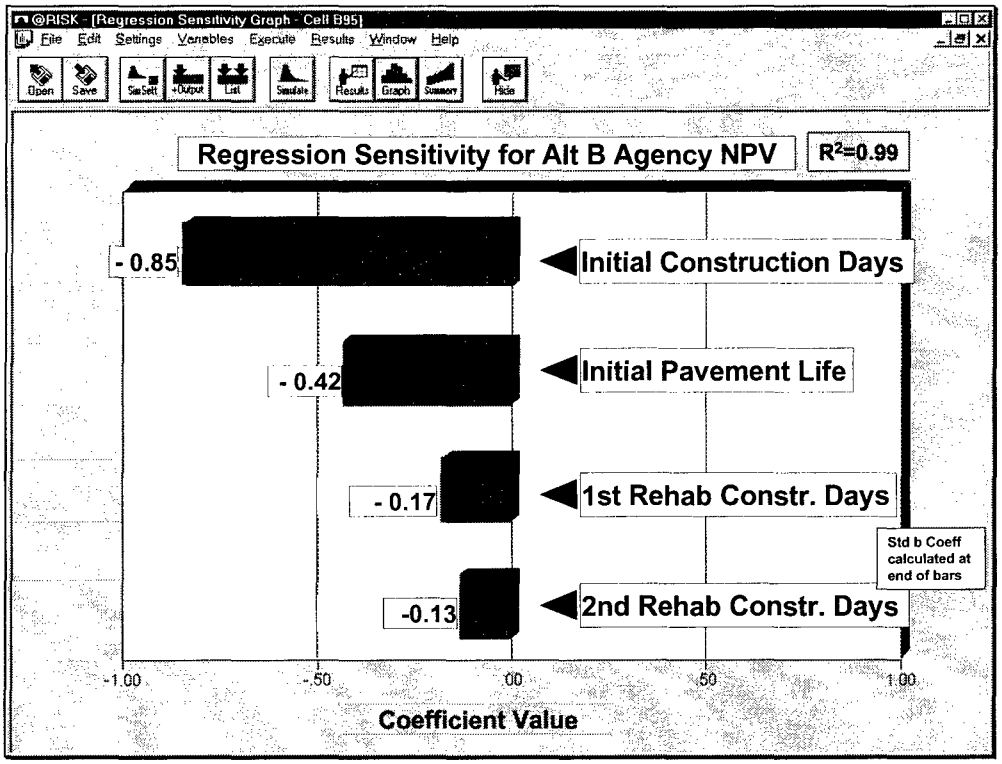
21


Alt-A Agency NPV
Rank
Graph
Hide
Regression Sensitivity
Rank Correlation
R²=0.992
Sensitivity to Inputs
Rank
Cell
Name
Sensitivity R²=0.992
Rank Correlation Coefficient
# 1 Alt A Initial Pavement Life -0.817 -0.807
# 2 Alt A Initial Constr. Days -0.404 -0.382
# 3 Alt A 1st Rehab Life -0.277 -0.247
# 4 Alt A 2nd Rehab Life -0.187 -0.181
# 5 Alt A 1st Rehab Const. Days -0.183 -0.171
Output Variables
Input Distribution
Standard b Coefficient
Statistics
Data
Sensitivity
Scenarios

22


@RISK - [Regression Sensitivity Graph - Cell B94]
File Edit Settings Variables Execute Results Window Help
Regression Sensitivity for Alt A Agency NPV
R²=0.99
-0.82
Initial Pavement Life
-0.40
Initial Constr. Days
-0.28
1st Rehab Life
-0.19
2nd Rehab Life
-0.18
1st Rehab Constr. Days
Std b Coeff calculated at end of bars
-1.00
-.50
.00
.50
1.00
Coefficient Value

23




24

## Sensitivity Observations

*Agency Costs ...*

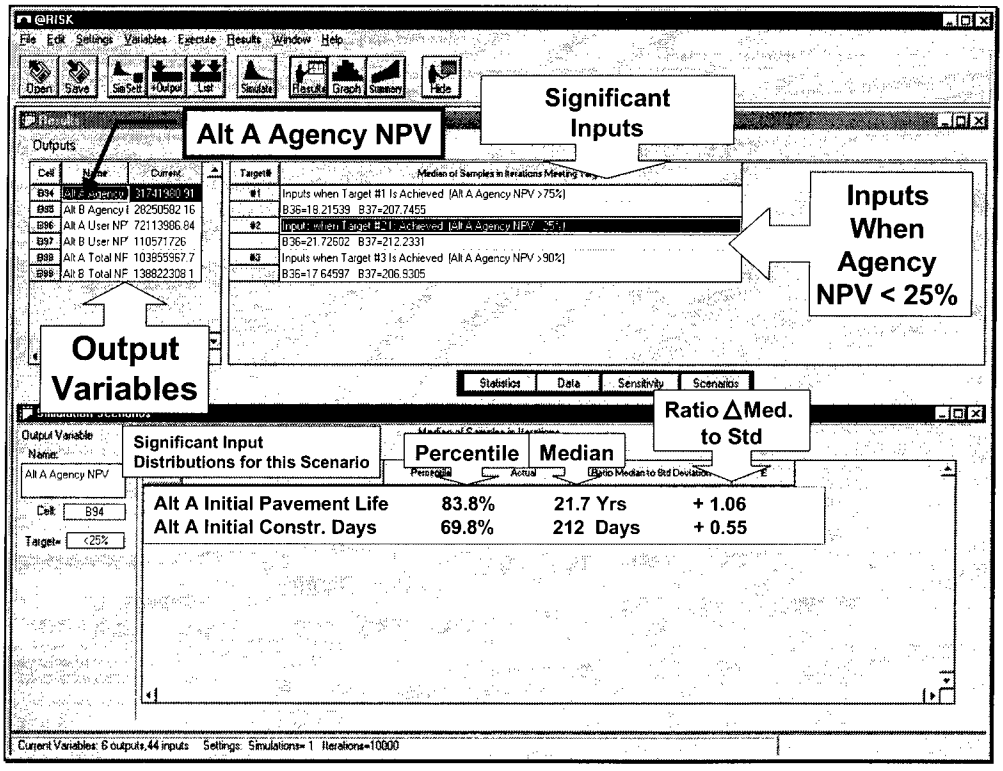
- Alternative A
  - Initial Pavement Life has the greatest influence on Agency NPV
- Alternative B
  - Initial Construction Days has the greatest influence on Agency NPV

25

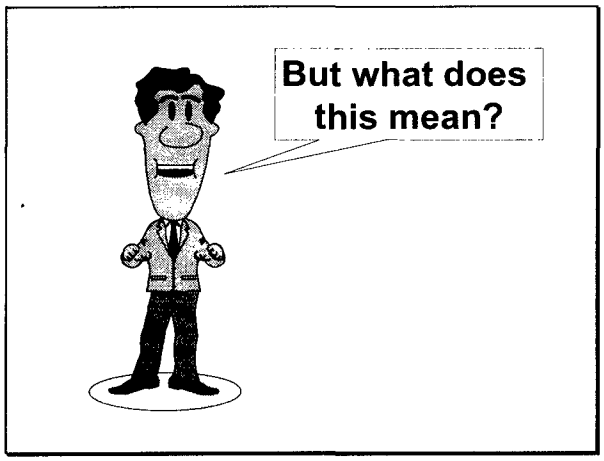
## Agency Cost

- Probability
- Sensitivity
- Scenario Analysis

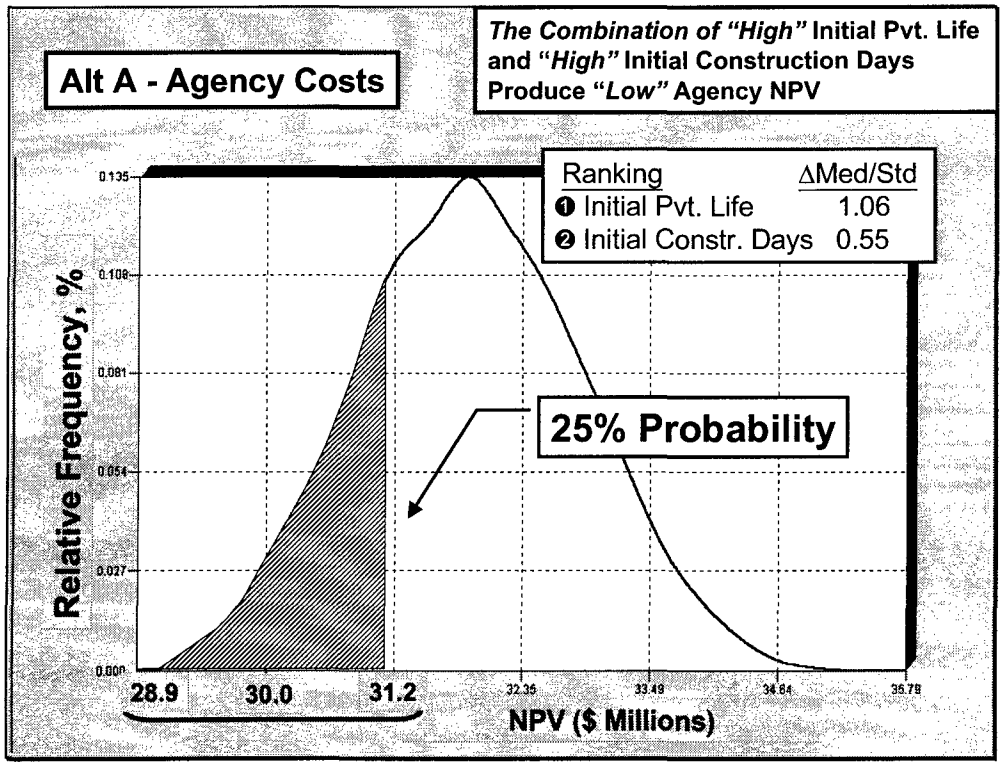
26



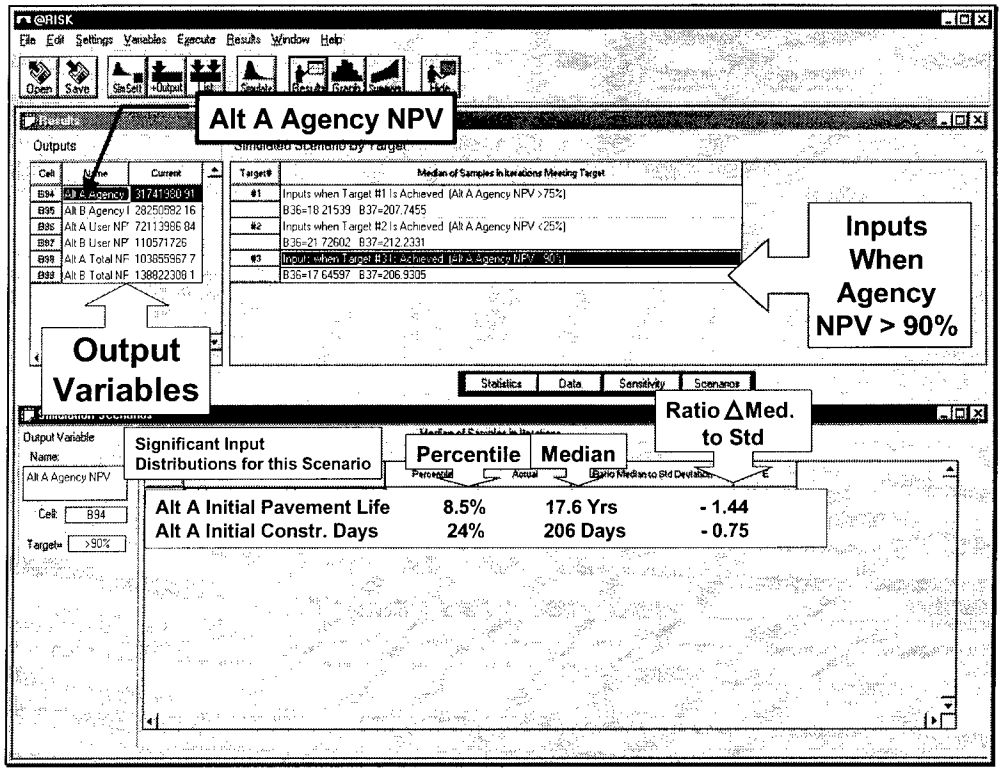
27


But what does this mean?

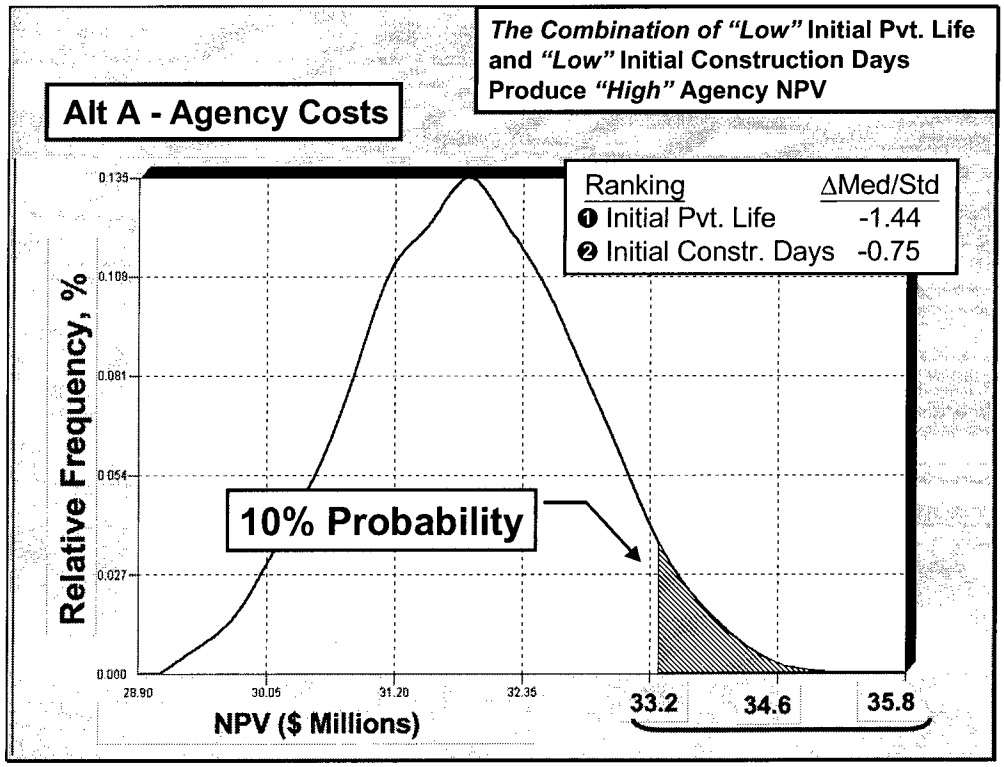
28


Alt A - Agency Costs
The Combination of "High" Initial Pvt. Life and "High" Initial Construction Days Produce "Low" Agency NPV
Ranking ΔMed/Std
❶ Initial Pvt. Life 1.06
❷ Initial Constr. Days 0.55
25% Probability
Relative Frequency, %
0.135
0.108
0.081
0.054
0.027
0.000
28.9
30.0
31.2
32.35
33.49
34.64
35.78
NPV ($ Millions)

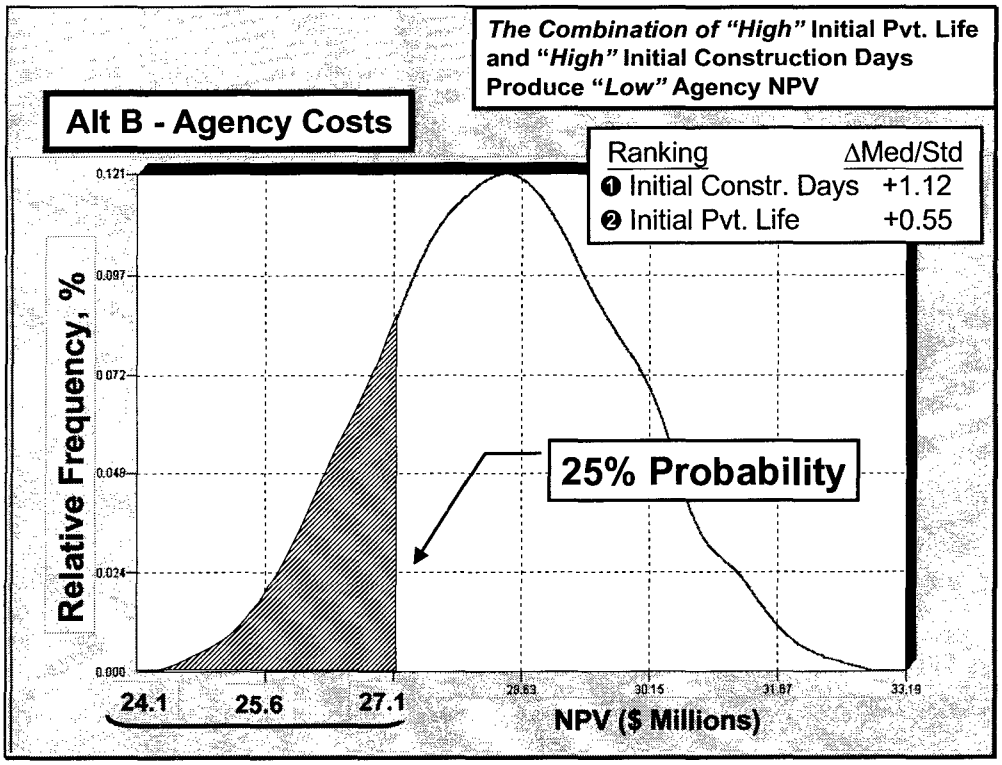
29


Alt A Agency NPV
Output Variables
Inputs When Agency NPV > 90%
Ratio ΔMed. to Std
Significant Input Distributions for this Scenario
Percentile
Median
Alt A Initial Pavement Life 8.5% 17.6 Yrs - 1.44
Alt A Initial Constr. Days 24% 206 Days - 0.75

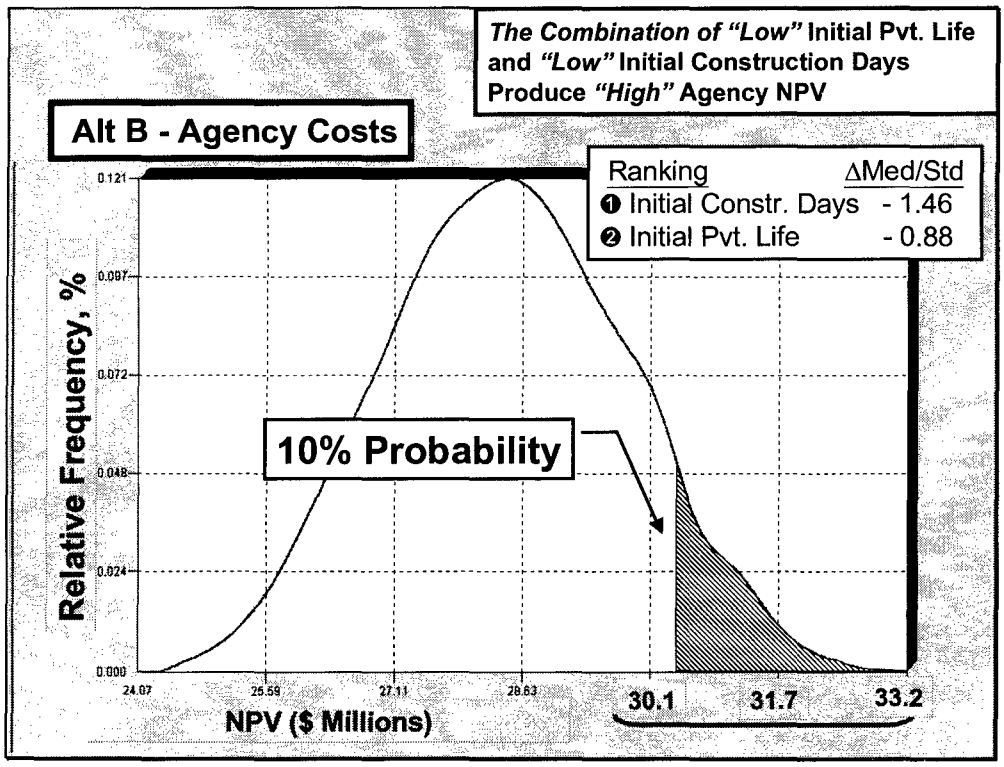
30


The Combination of "Low" Initial Pvt. Life and "Low" Initial Construction Days Produce "High" Agency NPV
Alt A - Agency Costs
Ranking ΔMed/Std
❶ Initial Pvt. Life -1.44
❷ Initial Constr. Days -0.75
Relative Frequency, %
0.135
0.108
0.081
0.054
0.027
0.000
10% Probability
28.90
30.05
31.20
32.35
33.2
34.6
35.8
NPV ($ Millions)

31


The Combination of "High" Initial Pvt. Life and "High" Initial Construction Days Produce "Low" Agency NPV
Alt B - Agency Costs
Ranking ΔMed/Std
❶ Initial Constr. Days +1.12
❷ Initial Pvt. Life +0.55
Relative Frequency, %
0.121
0.097
0.072
0.049
0.024
0.000
25% Probability
24.1
25.6
27.1
28.63
30.15
31.67
33.19
NPV ($ Millions)

32


The Combination of "Low" Initial Pvt. Life and "Low" Initial Construction Days Produce "High" Agency NPV
Alt B - Agency Costs
Ranking ΔMed/Std
❶ Initial Constr. Days - 1.46
❷ Initial Pvt. Life - 0.88
Relative Frequency, %
0.121
0.097
0.072
0.048
0.024
0.000
10% Probability
24.07
25.59
27.11
28.63
30.1
31.7
33.2
NPV ($ Millions)

33

## Scenario Analysis Observations

***For Alt A & B The Combination of ....***

- *"High"* Initial Pvt. Life and "High" Initial Construction Days Produce "Low" [< 25%] Agency Costs
- *"Low"* Initial Pvt. Life and "Low" Initial Construction Costs Produce "High" [>90%] Agency Costs

34

## Scenario Analysis Observations Cont'd.

Alternative A ...

- Initial Pavement Life is more significant than Initial Constr. days in both scenarios.

35

## Scenario Analysis Observations Cont'd.

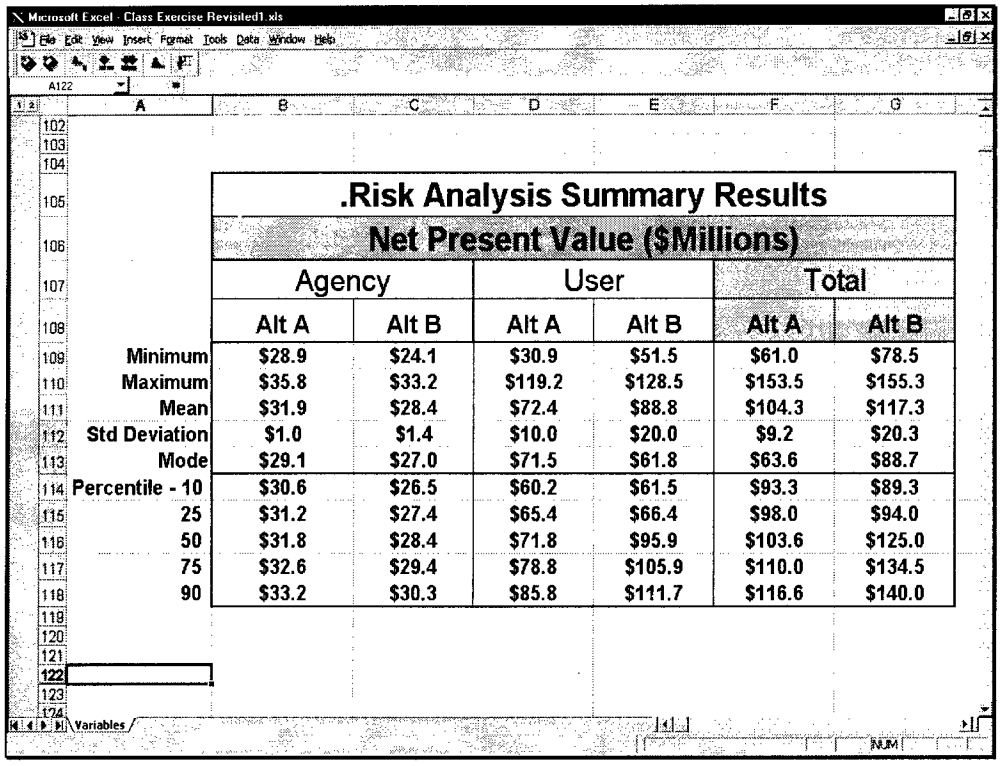
Alternative B ...

- Initial Constr. Days is more significant than Initial Pavement Life in both scenarios.

36

# User Costs

37




.Risk Analysis Summary Results

Net Present Value ($Millions)

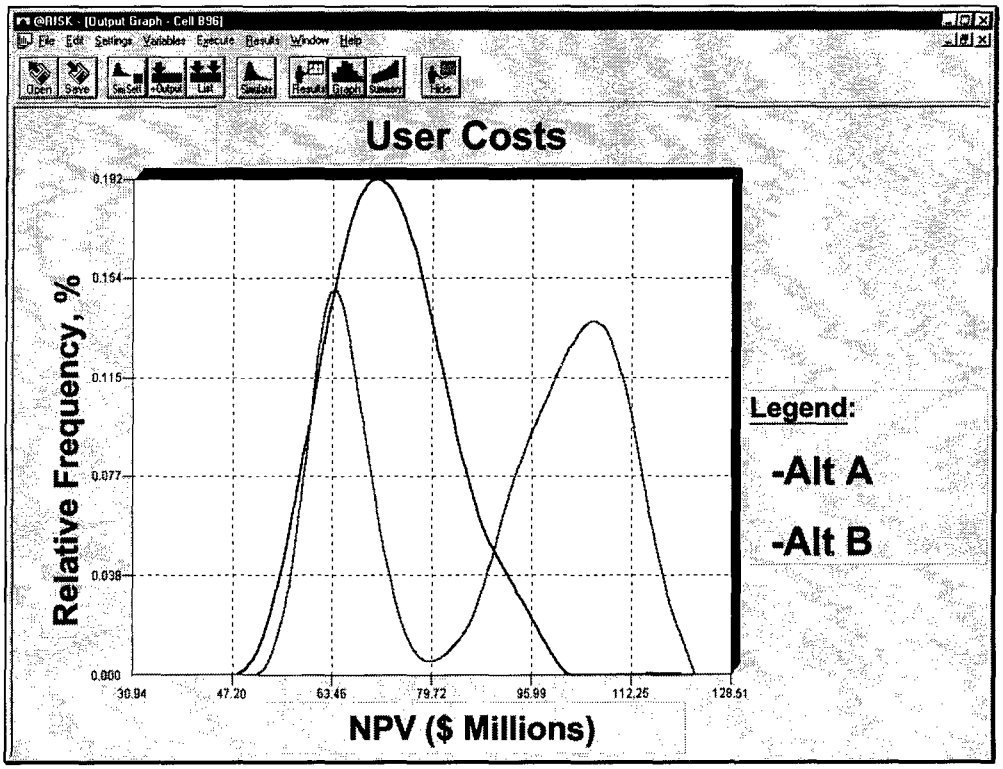
| | Agency | | User | | Total | |
|---|---|---|---|---|---|---|
| | Alt A | Alt B | Alt A | Alt B | Alt A | Alt B |
| Minimum | $28.9 | $24.1 | $30.9 | $51.5 | $61.0 | $78.5 |
| Maximum | $35.8 | $33.2 | $119.2 | $128.5 | $153.5 | $155.3 |
| Mean | $31.9 | $28.4 | $72.4 | $88.8 | $104.3 | $117.3 |
| Std Deviation | $1.0 | $1.4 | $10.0 | $20.0 | $9.2 | $20.3 |
| Mode | $29.1 | $27.0 | $71.5 | $61.8 | $63.6 | $88.7 |
| Percentile - 10 | $30.6 | $26.5 | $60.2 | $61.5 | $93.3 | $89.3 |
| 25 | $31.2 | $27.4 | $65.4 | $66.4 | $98.0 | $94.0 |
| 50 | $31.8 | $28.4 | $71.8 | $95.9 | $103.6 | $125.0 |
| 75 | $32.6 | $29.4 | $78.8 | $105.9 | $110.0 | $134.5 |
| 90 | $33.2 | $30.3 | $85.8 | $111.7 | $116.6 | $140.0 |

38

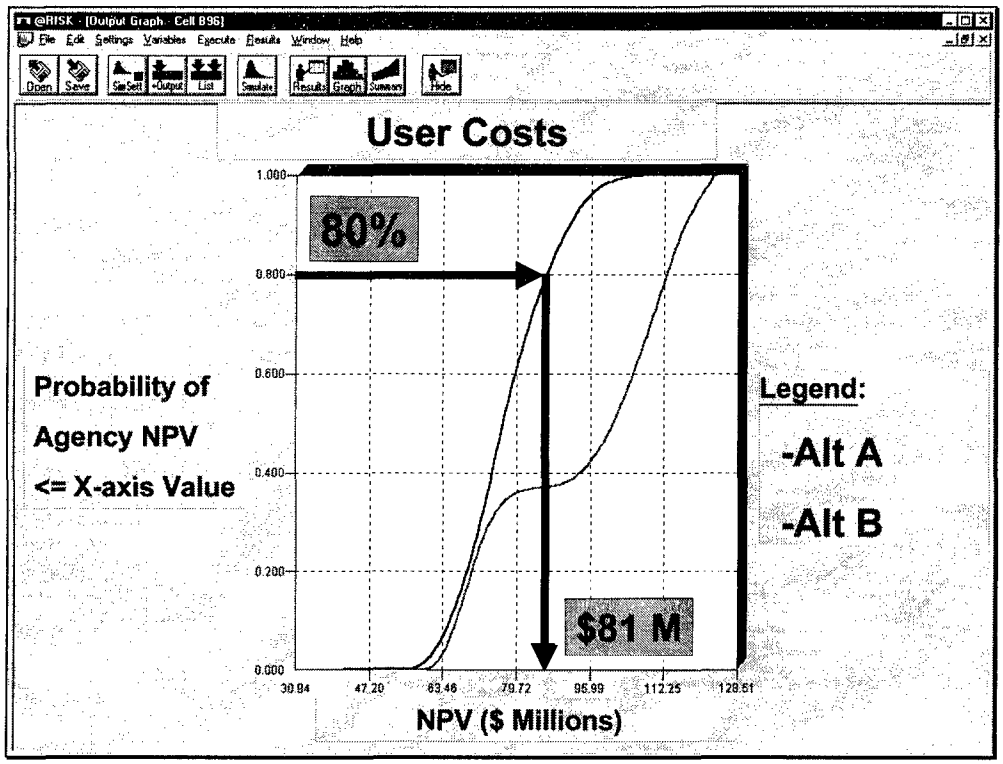
## User Costs

- Probability
- Sensitivity
- Scenario Analysis

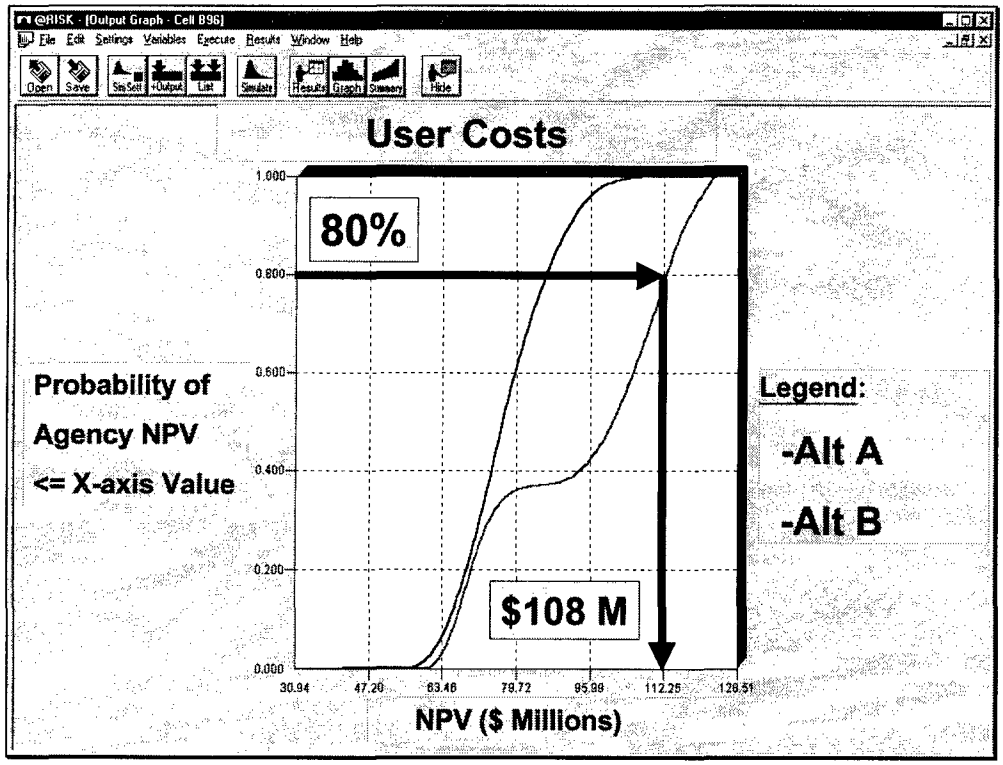
39



40


@RISK - [Output Graph - Cell B96]
File Edit Settings Variables Execute Results Window Help
Open Save SimSett +Output List Simulate Results Graph Summary Hide
User Costs
1.000
0.800
0.600
0.400
0.200
0.000
80%
$81 M
30.94 47.20 63.46 79.72 95.99 112.25 128.51
NPV ($ Millions)
Probability of
Agency NPV
<= X-axis Value
Legend:
-Alt A
-Alt B

41


@RISK - [Output Graph - Cell B96]
File Edit Settings Variables Execute Results Window Help
Open Save SimSett +Output List Simulate Results Graph Summary Hide
User Costs
1.000
0.800
0.600
0.400
0.200
0.000
80%
$108 M
30.94 47.20 63.46 79.72 95.99 112.25 128.51
NPV ($ Millions)
Probability of
Agency NPV
<= X-axis Value
Legend:
-Alt A
-Alt B

42

## Probability Observations

User Costs ...

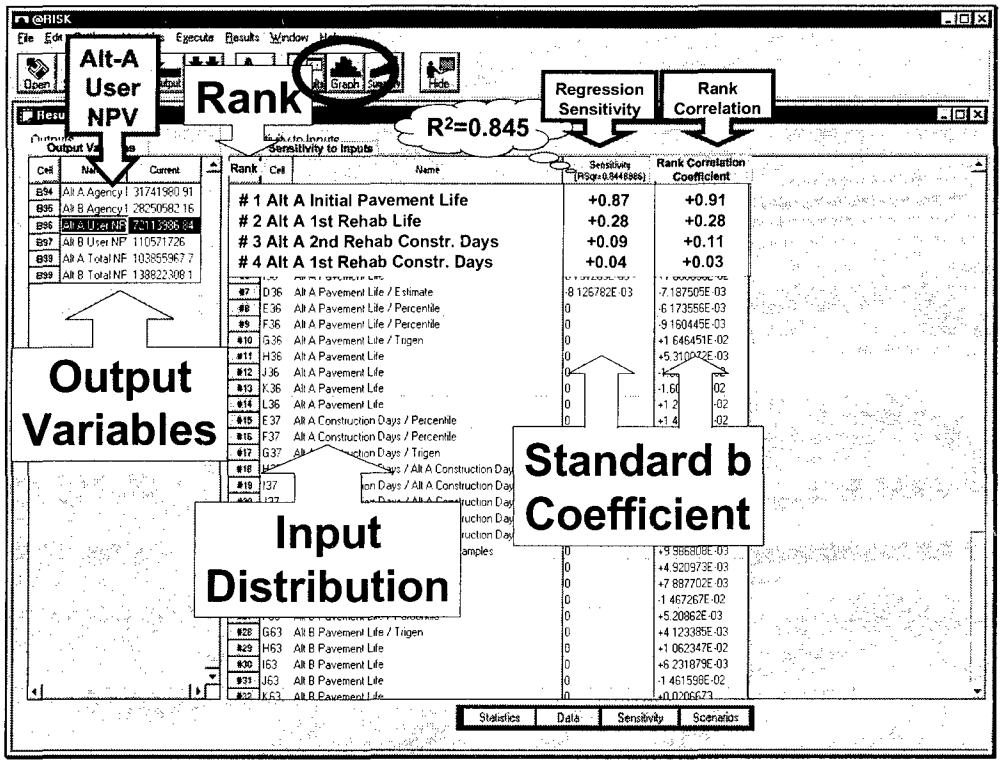
- At *any* given level of reliability Alt-A is *less* expensive than Alt-B.
- Alt-B is a *Bi-modal* Distribution
- Alt-B is *twice* as variable as Alt-A

43

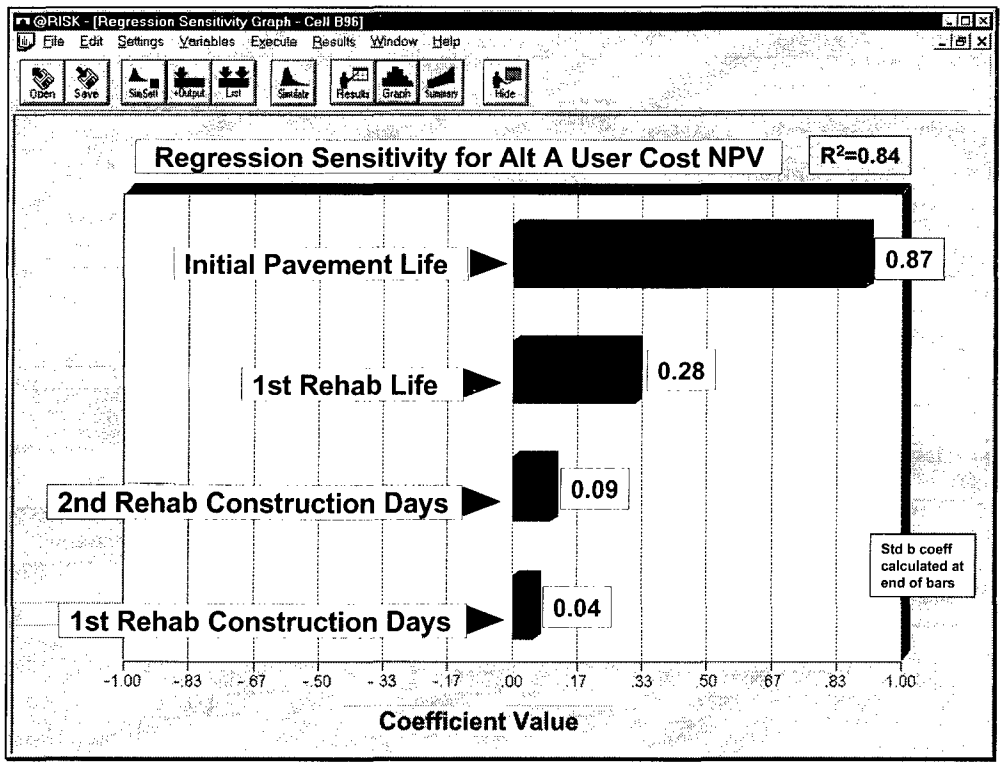
## User Costs

- Probability
- Sensitivity

44


Alt-A User NPV
Rank
Regression Sensitivity
Rank Correlation
R²=0.845
Output Variables
Standard b Coefficient
Input Distribution
# 1 Alt A Initial Pavement Life +0.87 +0.91
# 2 Alt A 1st Rehab Life +0.28 +0.28
# 3 Alt A 2nd Rehab Constr. Days +0.09 +0.11
# 4 Alt A 1st Rehab Constr. Days +0.04 +0.03

45


@RISK - [Regression Sensitivity Graph - Cell B96]
Regression Sensitivity for Alt A User Cost NPV
R²=0.84
Initial Pavement Life
0.87
1st Rehab Life
0.28
2nd Rehab Construction Days
0.09
1st Rehab Construction Days
0.04
Std b coeff calculated at end of bars
-1.00 -.83 -.67 -.50 -.33 -.17 .00 .17 .33 .50 .67 .83 1.00
Coefficient Value

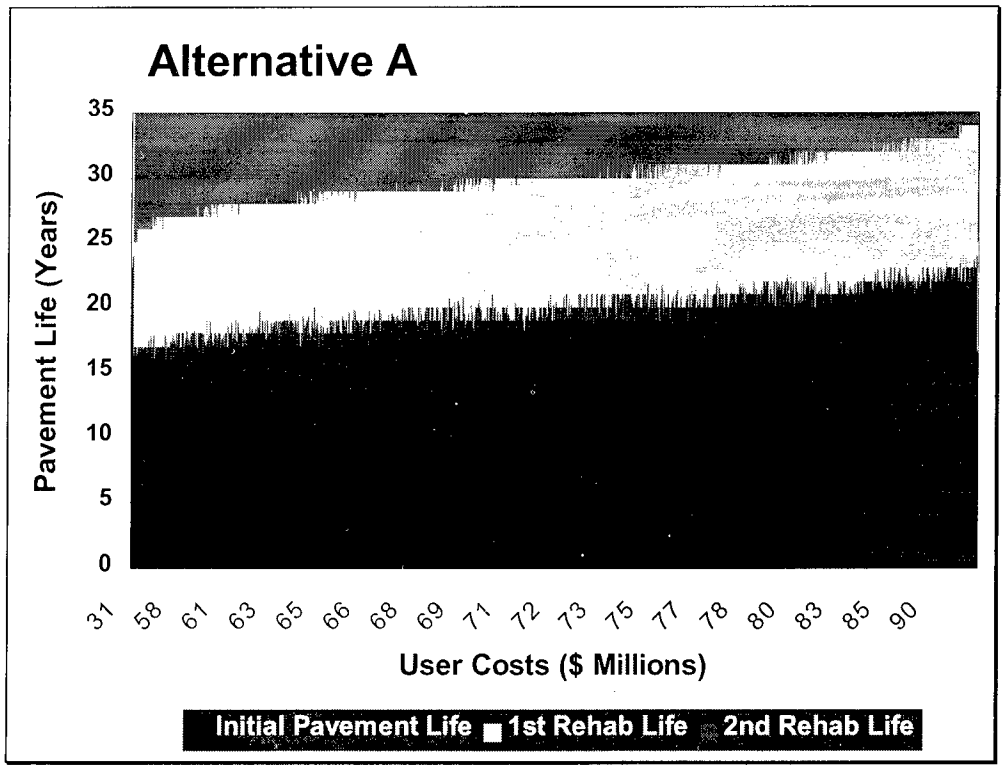
46

The Graph says ...
When Initial Pavement Life Samples High ...

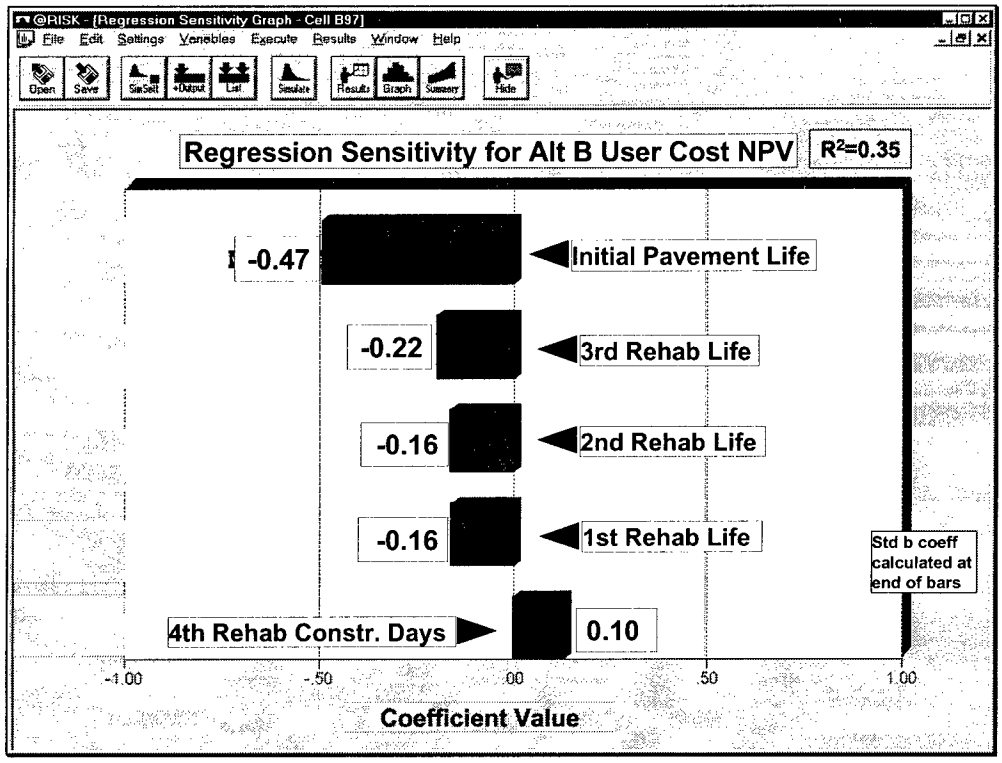
High User Costs are Produced.

Does this make sense?

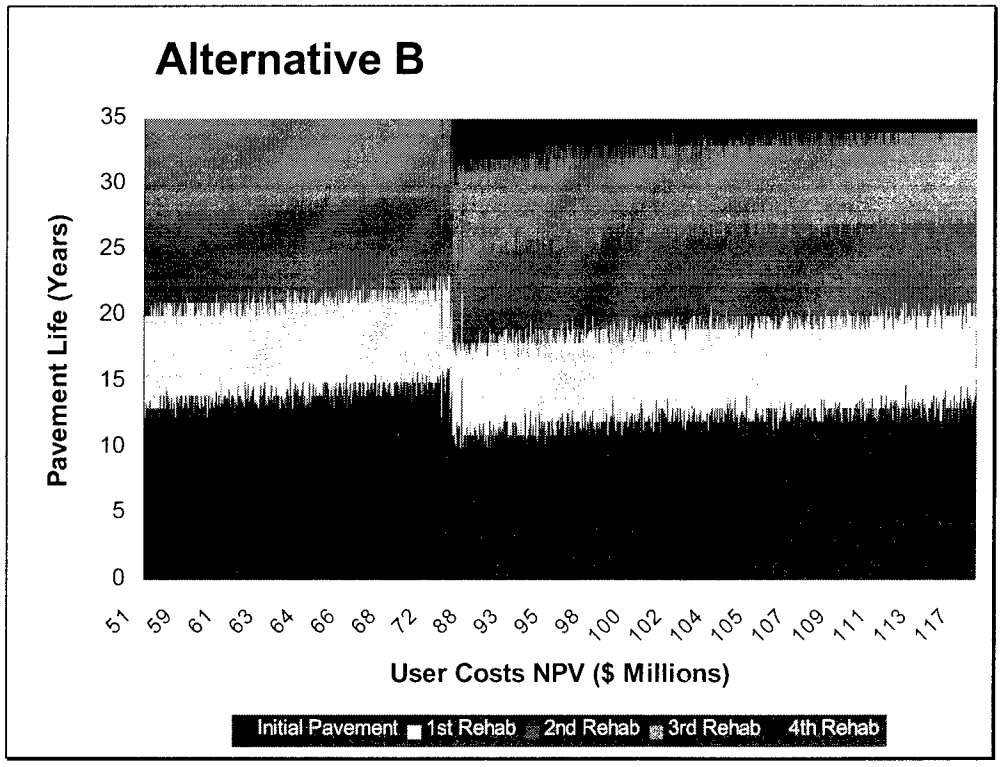
47



48


@RISK - [Regression Sensitivity Graph - Cell B97]
File Edit Settings Variables Execute Results Window Help
Open Save SimSett +Output List Simulate Results Graph Summary Hide
Regression Sensitivity for Alt B User Cost NPV
R²=0.35
-0.47
Initial Pavement Life
-0.22
3rd Rehab Life
-0.16
2nd Rehab Life
-0.16
1st Rehab Life
Std b coeff calculated at end of bars
4th Rehab Constr. Days
0.10
-1.00
-.50
.00
.50
1.00
Coefficient Value

49


Alternative B
Pavement Life (Years)
35
30
25
20
15
10
5
0
51 59 61 63 64 66 68 72 88 93 95 98 100 102 104 105 107 109 111 113 117
User Costs NPV ($ Millions)
Initial Pavement
1st Rehab
2nd Rehab
3rd Rehab
4th Rehab

50

## Sensitivity Observations

*For both Alt A & B User Costs ...*

- Initial Pavement Life has the greatest influence

51

## Sensitivity Observations Cont'd

Alternative A

- The variability of pavement life was such that two rehabs *always* occurred during analysis period
- As a result lower pavement lives produced lower user costs.

52

## Sensitivity Observations Cont'd

Alternative B

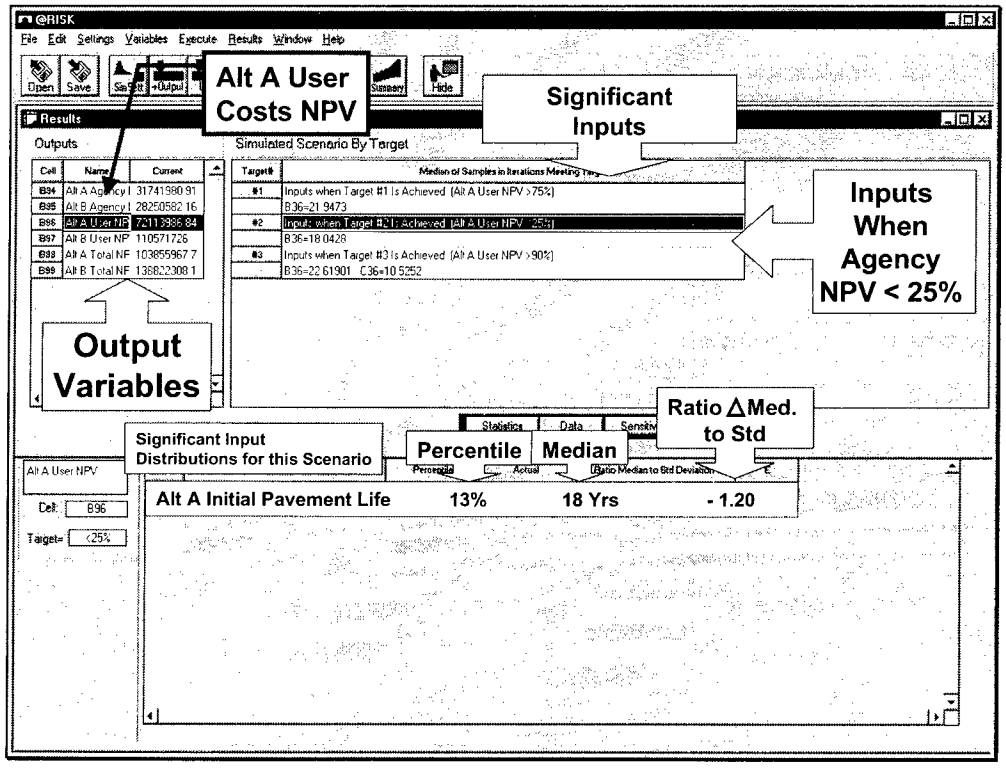
- The variability of pavement life was such that 3 and 4 rehabs occurred during analysis period
- This caused a Bi-modal Distribution
- As a result lower pavement lives produced higher user costs.

53

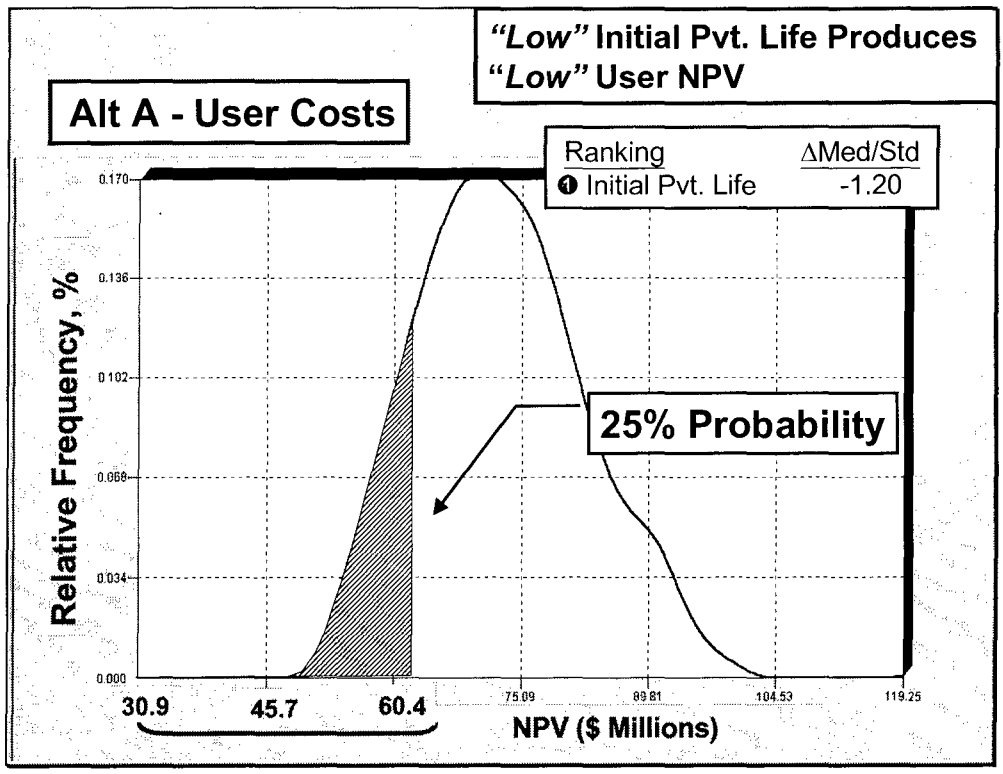
## User Costs

- Probability
- Sensitivity
- Scenario Analysis

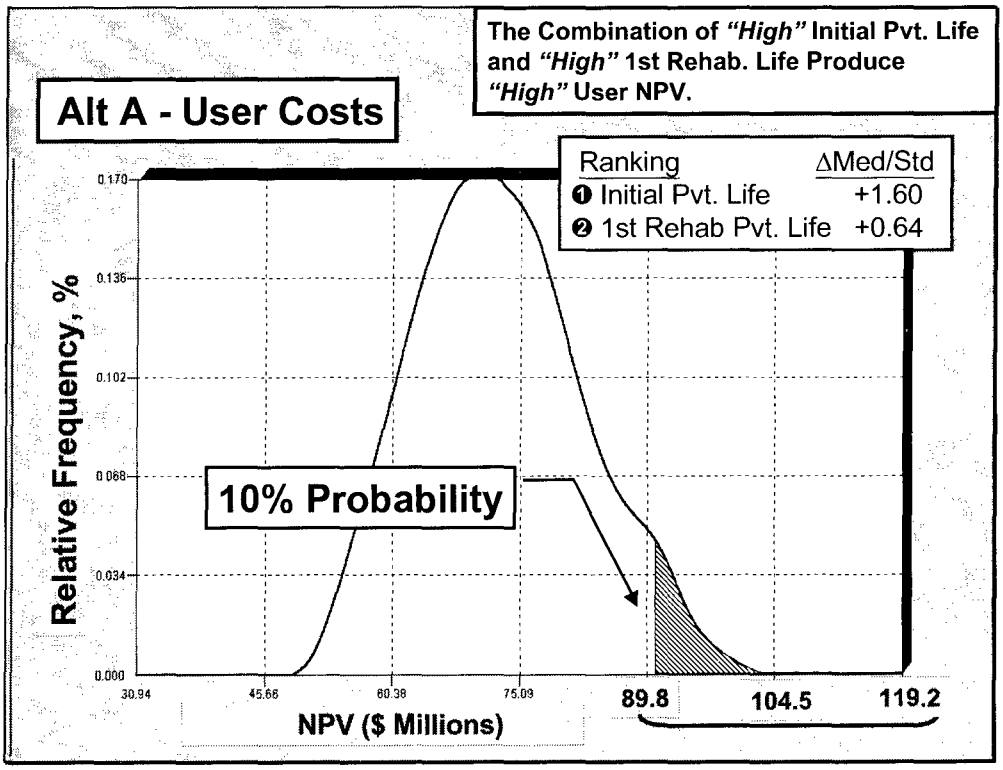
54



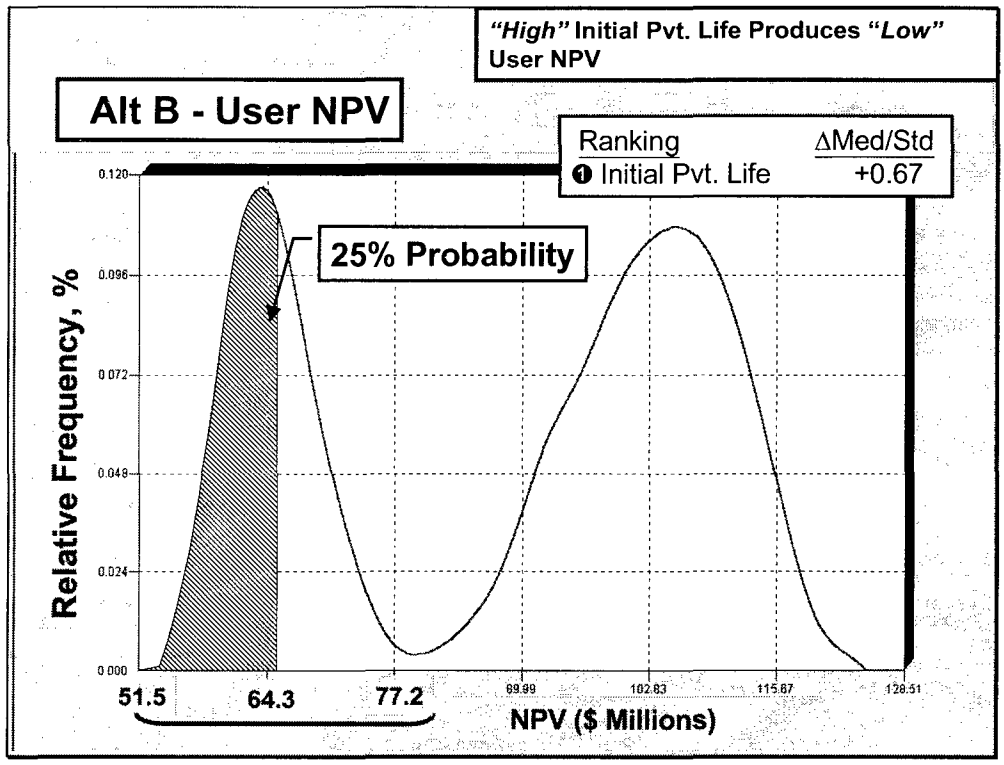
55


"Low" Initial Pvt. Life Produces "Low" User NPV
Alt A - User Costs
Ranking
ΔMed/Std
❶ Initial Pvt. Life
-1.20
25% Probability
Relative Frequency, %
0.170
0.136
0.102
0.068
0.034
0.000
30.9
45.7
60.4
75.09
89.81
104.53
119.25
NPV ($ Millions)

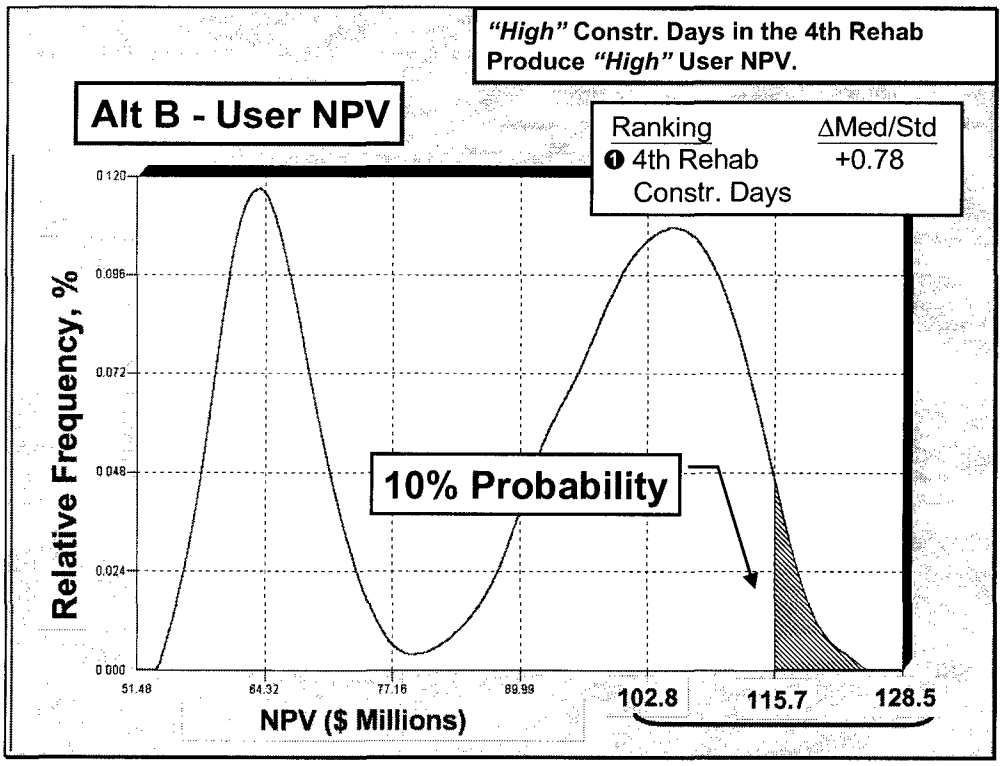
56


The Combination of "High" Initial Pvt. Life and "High" 1st Rehab. Life Produce "High" User NPV.
Alt A - User Costs
Ranking
ΔMed/Std
❶ Initial Pvt. Life
+1.60
❷ 1st Rehab Pvt. Life
+0.64
10% Probability
Relative Frequency, %
0.170
0.136
0.102
0.068
0.034
0.000
30.94
45.66
60.38
75.09
89.8
104.5
119.2
NPV ($ Millions)

57


"High" Initial Pvt. Life Produces "Low" User NPV
Alt B - User NPV
Ranking
ΔMed/Std
1 Initial Pvt. Life
+0.67
25% Probability
Relative Frequency, %
0.120
0.096
0.072
0.048
0.024
0.000
51.5
64.3
77.2
89.99
102.83
115.67
128.51
NPV ($ Millions)

58


"High" Constr. Days in the 4th Rehab Produce "High" User NPV.
Alt B - User NPV
Ranking
ΔMed/Std
1 4th Rehab Constr. Days
+0.78
10% Probability
Relative Frequency, %
0.120
0.096
0.072
0.048
0.024
0.000
51.48
64.32
77.16
89.99
102.8
115.7
128.5
NPV ($ Millions)

59

## Scenario Analysis Observations

*User Costs* Alternative A

- "Low" Initial Pavement Life produces Low User NPV
- The Combination of *"Low"* Initial Pvt. Life and *"High"* 1st Rehab. Life Produce Low User NPV

60

## Scenario Analysis Observations

*User Costs* Alternative B

- "High" Initial Pavement Life produces Low User NPV
- "High" Constr. Days in the 4th Rehab produce "High" User Costs.

61

Which Alternative would you select?

Must define Agency's tolerance for risk.

62

## If User Costs Dominate … Reevaluate Alternatives

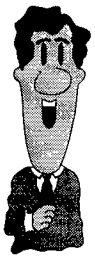
- Decrease construction time (accelerate contractor production)
- Lane Rental (A+B Bidding)
- Temporary bypass
- Increase shoulder strength
- Other?

63

## End Session

1

# Presentation Techniques



2

## Know Your Audience

- Does your audience understand ...
  - LCCA?
  - Discounting?
  - User costs?
  - Value of time?

3

## You need to know ...

- Do they need a Risk Primer?
- Do they buy into the risk analysis approach?
- Do they buy-in to your analysis

4

## Here's Some Advice ...

- Don't bury them in statistics
- List significant inputs
  - Identify what's driving the tails of the distribution ...
  - Can you control it?
- Show results graphically

5

## Report

- One page summary (???)
- Supporting documentation

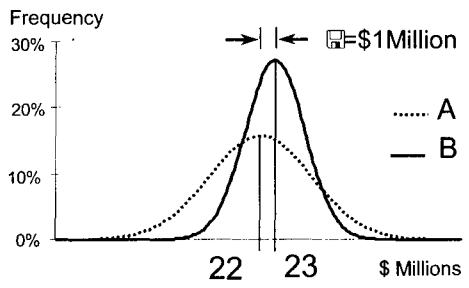
6

## One Page Summary

- Inputs: List uncertain variables
- Outputs:
  - Histogram & Cumulative
  - Mean, Std. Dev., Percentiles
- Analysis of results
  - Tornado graphs, Scenario analysis
- Recommendations
  - Include level of risk

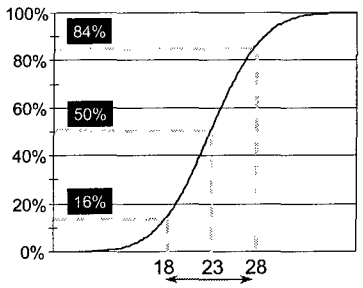
7

## Histogram -




8

## Cumulative -



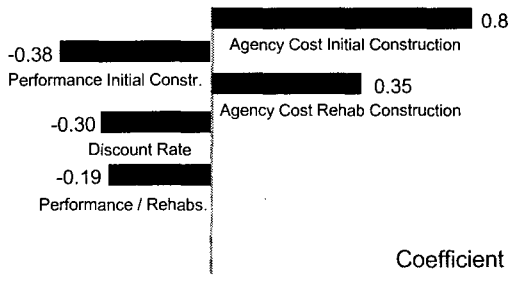

84% of all values fall below 28

50% of all values fall below 23

16% of all values fall below 18

9

## Regression Sensitivity (Tornado Graphs)



10

## Supporting Documentation

- Distributions with supporting justifications
- Structure and layout of model
- Sensitivity analysis of proposed distributions
- Analysis of uncertain events

11

## End Session

1

# Benefits and Implementation

2

## Benefits of LCCA

- Informed decisions
- Sensitivity to user costs
- More effective use of resources
- Support funding requests

3

## Benefits of LCCA Con't

- Objective basis for resource allocation
  - Network, project, & design
- Assess funding consequences

4

## Benefits of Risk Analysis

- Better design strategies
- Improved design procedures
- Effective engineering input to policy decisions

5

## Benefits of RA Cont'd

- Expose areas of uncertainty
- Quantify risk
- Opportunity for mitigating action
- Improved credibility
- Assess impact of risk on investment decisions
- Avoid disasters

6

## Benefits of RA Cont'd

- Determine significance of difference between alternatives
- Examine influence of underlying variables on final results
- Evaluate all possible outcomes

7

## Caveats

- New concept
- Requires statistical background
- Computer intensive
  - Proprietary software
  - Complex models
- Requires risk management "buy in" by senior executives

8

## Implementation

9

## Obstacles

- Lack of awareness
- Resistance to change
- Time pressures
- Lack of communication
- Unavailability of resources

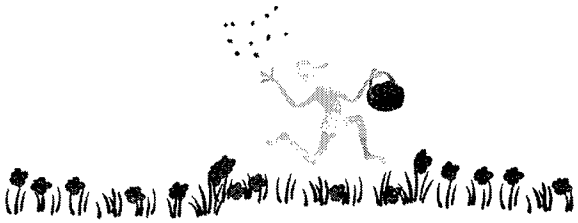
10

## Implementation Steps

- Awareness
- Change
- Communication
- Resources

11

## Plant the Seed



12

## Four Stages of Learning

1. Unconscious Incompetence
2. Conscious Incompetence
3. Conscious Competence
4. Unconscious Competence

13

## Implementation Steps

- Identify a champion
- Understand classical LCCA
- Assess current procedures
- Determine data availability
- Tap expert opinion

14

## Probabilistic Champion

- Believer
- Well founded in LCCA
- Spreadsheet literate
- Time available

15

## Resources

- Equipment
- Software
- Personnel
- Training
- User groups

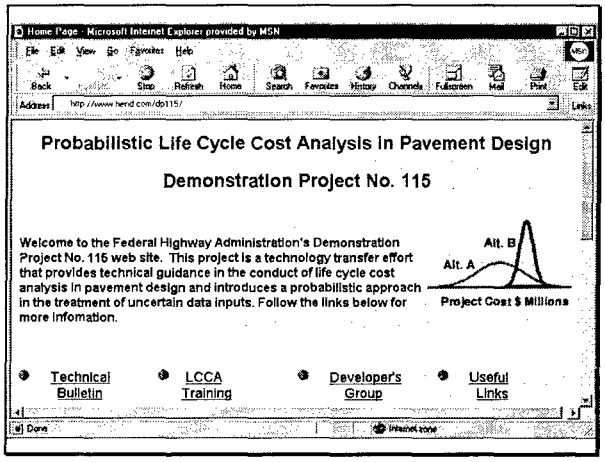
16

## Resources Con't

- DP 115 Case Study States
  - Two contacts per state
  - List of names & address available upon request
- DP 115 Web Site

  http://www.hend.com/dp115

17




18

## Top Management Support

- Establish objectives
- Provide policy input
- Provide resources
- Provide "Bureaucratic Clout"

19

## Steering Committee

- LCCA procedure
- Probabilistic approach

20

## Documentation

- Standardize SHA's approach to LCCA
- Document SHA LCCA procedures
- Apply consistently

21

## End Session

1

# Workshop Summary

2

## Key Areas Covered

- Traditional LCCA
- User Cost
- Risk Analysis Approach

3

## Things to Remember

- LCCA decision support tool
- NHS LCCA requirements
- Document procedures
- Document inputs
- Dispose of all issues

4

## Recommendations

LCCA ...

- Long analysis periods
- Constant dollars
- Real discount rates (3-5%)
- NPV

5

## Recommendations

- Value of time
  - Passenger $10 - $13
  - Single Unit Trk $17 - $20
  - Combo Trk $21 - $24

6

## Recommendations

Agency Costs ...

- Include agency overhead
- Ignore sunk cost
- Don't sweat reactive maintenance and salvage value

7

## Recommendations

### User Costs ...

- Traffic grows
- Queuing cost dominate
- Hourly distributions key
- $ Value of time major influence
- Circuity can be major

8

Recommend a risk analysis approach in the treatment of uncertainty.

9

# The End

# Class Exercise No. 1
# Net Present Value

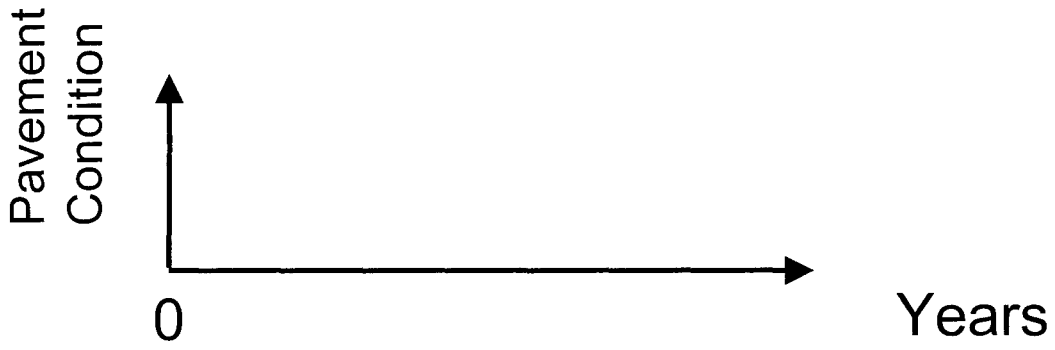
Compute the Net Present Value (NPV) for the following Alternative.

| | Initial Constr. | Rehab. |
|---|---|---|
| Design Period, (yrs) | 20 | 10 |
| Agency Cost ($ Millions) | 26 | 9 |
| Construction Period (days) | 210 | 105 |

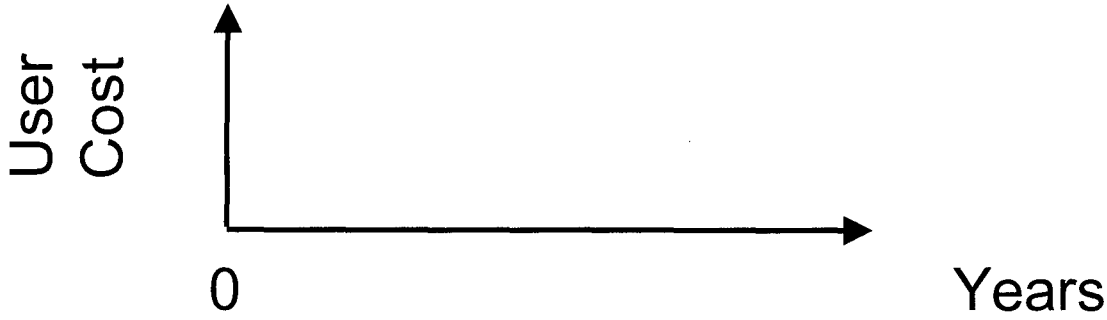
Assume the following:

| | |
|---|---|
| Analysis Period (yrs) | 30 |
| Daily Delay (Hours) | 3000 |
| Routine Maintenance | Insignificant |
| Discount Rate, % | 4 |
| Value of Time ($/hr) | 10 |

# Performance Curve




# Expenditure Streams

# User Cost Calculations

User Cost = Construction Days x Daily Delay x Value of Time

## Initial Construction

User Cost = _____ days x _____ hrs/day x _____$/ hr.

= $_____

## Rehabilitation

User Cost = _____ days x _____ hrs/day x _____$/ hr.

= $_____

$$NPV = InitialCost + \sum_{k=1}^{N} FutureCost\left[\frac{1}{(1+i)^{n_k}}\right]$$

Note: Quantity in brackets is present value factor from page 1.5.

# Agency Cost

NPV =

# User Cost

NPV =

# Present Value Factors

| Year n | Discount Rate, (i) | | | | |
|---|---|---|---|---|---|
| | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

# Class Exercise No. 2
# Net Present Value

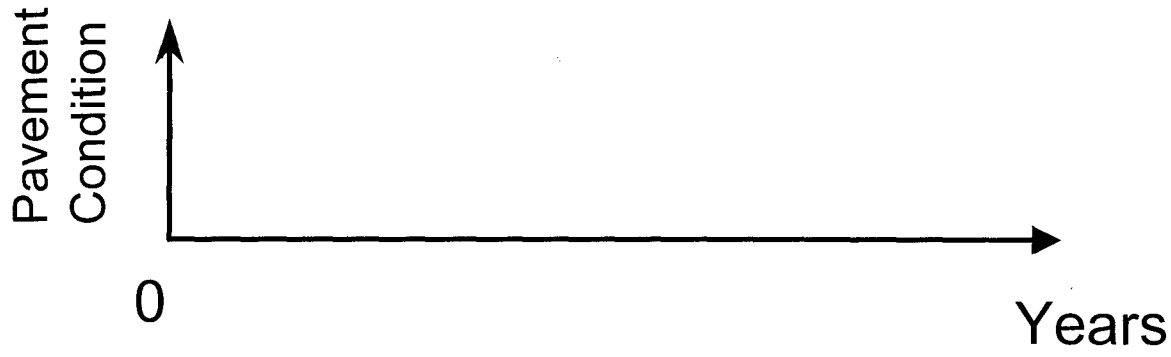
Compute the Net Present Value (NPV) for the following Alternative.

| | Initial Constr. | Rehab. |
|---|---|---|
| Design Period, (yrs) | 20 | 8 |
| Agency Cost ($ Millions) | 30 | 9 |
| Construction Period (days) | 200 | 80 |

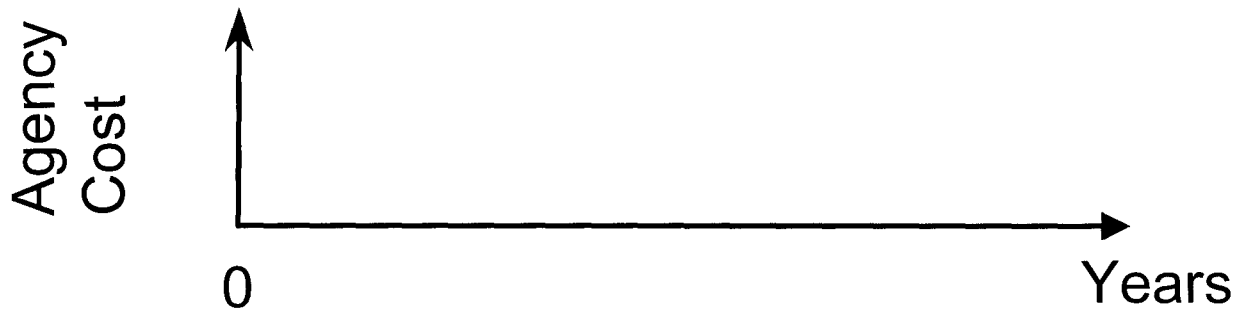
Assume the following:

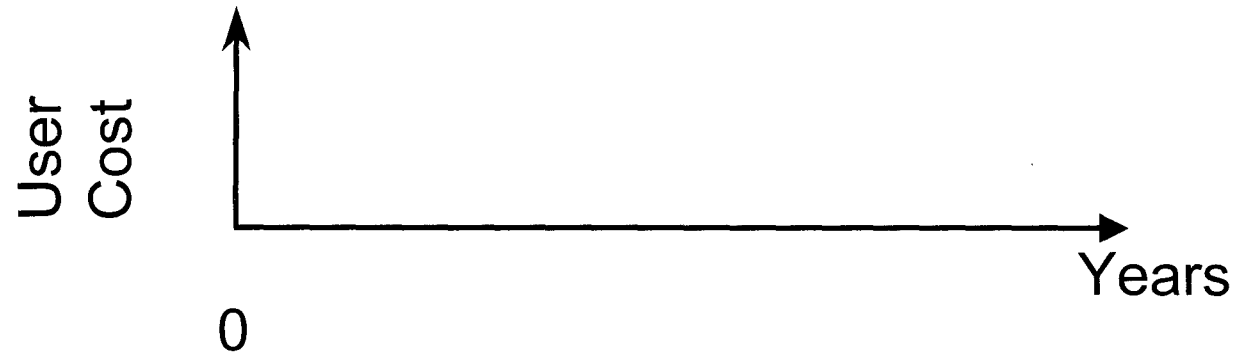
| | |
|---|---|
| Analysis Period (yrs) | 30 |
| Daily Delay (Hours) | 4000 |
| Routine Maintenance | Insignificant |
| Discount Rate, % | 4 |
| Value of Time ($/hr) | 15 |

# Performance Curve




# Expenditure Streams



# User Cost Calculations

User Cost = Construction Days x Daily Delay x Value of Time

## Initial Construction

User Cost = _____ days x _____ hrs/day x _____$/ hr.

= $_____

## Rehabilitation

User Cost = _____ days x _____ hrs/day x _____$/ hr.

= $_____

$$NPV = InitialCost + \sum_{k=1}^{N} FutureCost\left[\frac{1}{(1+i)^{n_k}}\right]$$

Note: Quantity in brackets is present value factor from page 2.5.

# Agency Cost

NPV =

# User Cost

NPV =

# Present Value Factors

| Year n | Discount Rate, (i) | | | | |
|---|---|---|---|---|---|
| | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

# Class Exercise No. 3
# Work Zone User Cost

The eastbound lanes of a six-lane facility are undergoing rehabilitation. Figures 1 and 2 provide a layout of the work zone and the associated user cost components. The facility carries 95,000 vehicles per day of which 90% are passenger cars, 6% single unit trucks, and 4% combination unit trucks. The directional factor is 54% for the eastbound direction. A 7 mile work zone closing one lane will be in place 24 hours each day until construction is complete. It is estimated to take 75 days to complete construction. The upstream approach speed is posted at 55 mph and the speed through the work zone will be posted at 35 mph. The free flow capacity of the roadway is estimated at 2100 vehicles per hour per lane (vphpl) while the work zone capacity is estimated at 1400 vphpl. A capacity analysis of the work zone is shown in Table 1. This class exercise includes three separate problems identified below.

### Problem ❶

Determine the quantity of traffic associated with each work zone user cost component.

### Problem ❷

Determine the reduced speed delay to traverse the work zone and queue.

### Problem ❸

Calculate the user costs associated with the work zone.

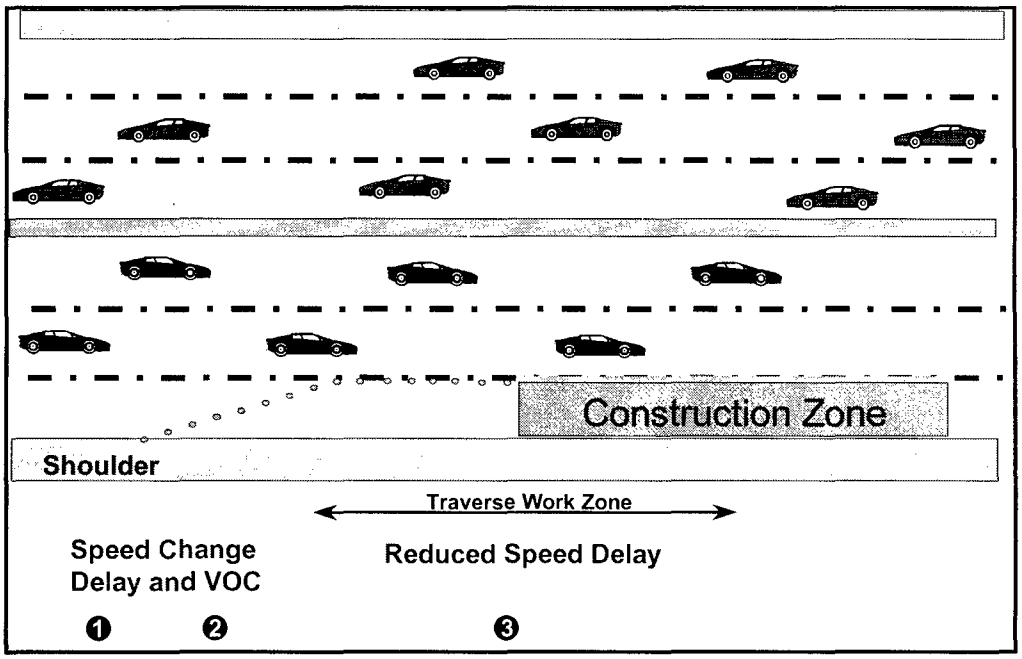



**Figure 1.** Eastbound Work Zone User Cost Components at Free Flow Conditions.

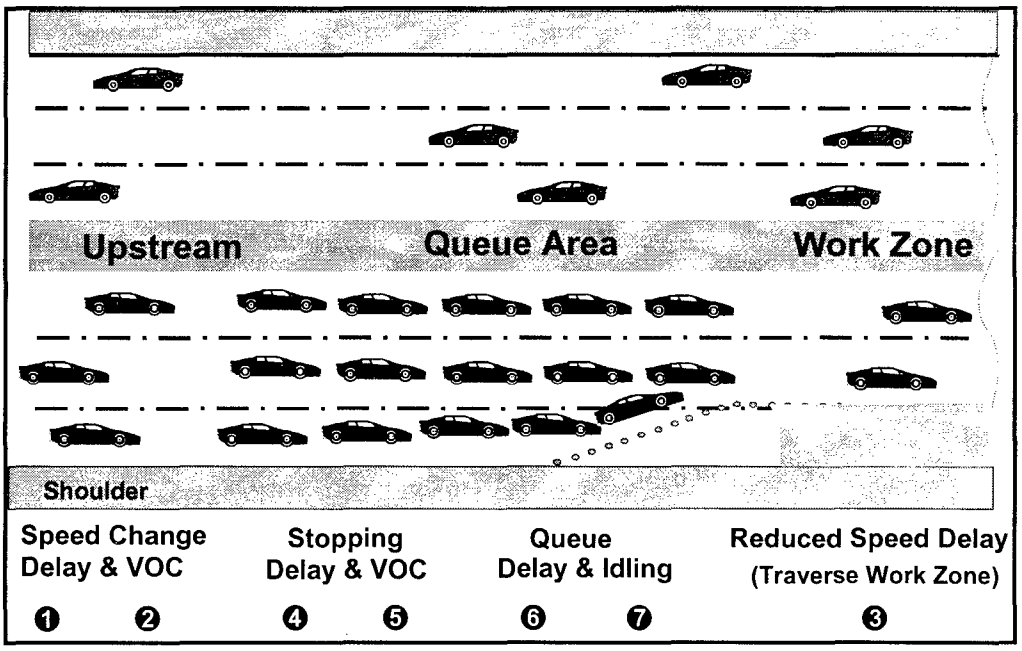



**Figure 2.** Eastbound Work Zone User Cost Components at Forced Flow Conditions.

**Table 1.** Capacity Analysis of Work Zone Operation.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Eastbound | | | | | AADT | 95,000 | | |
| Directional Factor | | | 54.0% | | | | Directional AADT | 51,300 | | |
| | | | Hrly | Vehicle | | Queuing | Culm. | Vehicles that ... | | |
| | | | Distri. | Demand | Capacity | Rate | Que Veh. | Stop | Traverse WZ | SlowDown |
| Hour | | | % | vph | vph | vph | | 55-0-55 | at 35 mph | 55-35-55 |
| 0 | - | 1 | 0.9 | 462 | 2,800 | (2,338) | 0 | 0 | 462 | 462 |
| 1 | - | 2 | 0.5 | 257 | 2,800 | (2,544) | 0 | 0 | 257 | 257 |
| 2 | - | 3 | 0.4 | 205 | 2,800 | (2,595) | 0 | 0 | 205 | 205 |
| 3 | - | 4 | 0.4 | 205 | 2,800 | (2,595) | 0 | 0 | 205 | 205 |
| 4 | - | 5 | 0.6 | 308 | 2,800 | (2,492) | 0 | 0 | 308 | 308 |
| 5 | - | 6 | 1.8 | 923 | 2,800 | (1,877) | 0 | 0 | 923 | 923 |
| 6 | - | 7 | 4.4 | 2,257 | 2,800 | (543) | 0 | 0 | 2,257 | 2257 |
| 7 | - | 8 | 6.2 | 3,181 | 2,800 | 381 | 381 | 3,181 | 3,181 | 0 |
| 8 | - | 9 | 5.7 | 2,924 | 2,800 | 124 | 505 | 2,924 | 2,924 | 0 |
| 9 | - | 10 | 5.1 | 2,616 | 2,800 | (184) | 321 | 2,616 | 2,616 | 0 |
| 10 | - | 11 | 5.2 | 2,668 | 2,800 | (132) | 189 | 2,668 | 2,668 | 0 |
| 11 | - | 12 | 5.6 | 2,873 | 2,800 | 73 | 261 | 2,873 | 2,873 | 0 |
| 12 | - | 13 | 6.0 | 3,078 | 2,800 | 278 | 539 | 3,078 | 3,078 | 0 |
| 13 | - | 14 | 5.9 | 3,027 | 2,800 | 227 | 766 | 3,027 | 3,027 | 0 |
| 14 | - | 15 | 6.4 | 3,283 | 2,800 | 483 | 1,249 | 3,283 | 3,283 | 0 |
| 15 | - | 16 | 7.4 | 3,796 | 2,800 | 996 | 2,246 | 3,796 | 3,796 | 0 |
| 16 | - | 17 | 7.8 | 4,001 | 2,800 | 1,201 | 3,447 | 4,001 | 4,001 | 0 |
| 17 | - | 18 | 7.5 | 3,848 | 2,800 | 1,048 | 4,494 | 3,848 | 3,848 | 0 |
| 18 | - | 19 | 5.9 | 3,027 | 2,800 | 227 | 4,721 | 3,027 | 3,027 | 0 |
| 19 | - | 20 | 4.9 | 2,514 | 2,800 | (286) | 4,435 | 2,514 | 2,514 | 0 |
| 20 | - | 21 | 4.0 | 2,052 | 2,800 | (748) | 3,687 | 2,052 | 2,052 | 0 |
| 21 | - | 22 | 3.3 | 1,693 | 2,800 | (1,107) | 2,580 | 1,693 | 1,693 | 0 |
| 22 | - | 23 | 2.4 | 1,231 | 2,800 | (1,569) | 1,011 | 1,231 | 1,231 | 0 |
| 23 | - | 24 | 1.7 | 872 | 2,800 | (1,928) | 0 | 457 | 872 | 415 |
| | | Total | 100 | 51,300 | | | | 46,268 | 51,300 | 5,032 |

***Note:*** The number of vehicles required to stop (55-0-55 mph) during the last hour (23-24) is prorated based on the amount of time required to clear the queue remaining in the previous hour.

# Problem No. 1

Using the data from the 24 hour capacity analysis shown in Table 1 quantify the traffic affected in each of the following cost components for the duration of the project.

❶ **WZ Speed Change Delay (Free Flow)**
**55 ➡ 35 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

❷ **WZ Speed Change VOC (Free Flow)**
**55 ➡ 35 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

❸ **Reduced Speed Delay Base Case (Free Flow)**
**35 vs 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

***Note:*** *Problem No. 1 continued on next page.*

# Problem No. 1 Continued

❹ **Queue Stopping Delay (Forced Flow)**
**55 ➡ 0 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

❺ **Queue Stopping VOC (Forced Flow)**
**55 ➡ 0 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

❻ **Queue Added Travel Delay**
**Queue Speed vs. 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

❼ **Queue Idle VOC**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | |
| 6% Single Unit | |
| 4% Combination | |

# Problem No. 2

Compute the reduced speed delay to traverse the work zone.

| | | Work Zone Length | Time |
|---|---|---|---|
| **Work Zone Speed** | _____ mph | _____ mi. | _____ hrs. |
| **Upstream Speed** | _____ mph | _____ mi. | _____ hrs. |
| **Ⓐ Increased Time to Traverse the Work Zone:** | | | _____ hrs. |

Compute the reduced speed delay to traverse the queue.

| Computation Step | | Value |
|---|---|---|
| ❶ Maximum number of queued vehicles | | |
| Queue Volume ($V_Q$) "Capacity of Work Zone" | | |
| Queue Capacity ($C_Q$) "Upstream Capacity" | | |
| $V_Q/C_Q$ | | |
| Queue Speed ($S_Q$) *(See Figure 3 Page 3.7)* | | |
| ❷ Work Zone Density ($V_Q/S_Q$) | | |
| Upstream Volume ($V_U$) "Demand at Max. No. Queued Vehicles" | | |
| Upstream Speed ($S_U$) | | |
| ❸ Upstream Density ($V_U/S_U$) | | |
| △ Density (❷ - ❸) | | |
| ❹ Maximum Queue Length (❶ / △ Density) | | |
| ❺ Average Queue Length (❹ / 2) | | |
| **Queue Travel Time** | ❻ ❺ /Queue Speed ($S_Q$) (hrs) | |
| | ❼ ❺ /Upstream Speed ($S_U$) (hrs) | |
| **Ⓑ Queue Delay (hrs) (❻ - ❼)** | | |

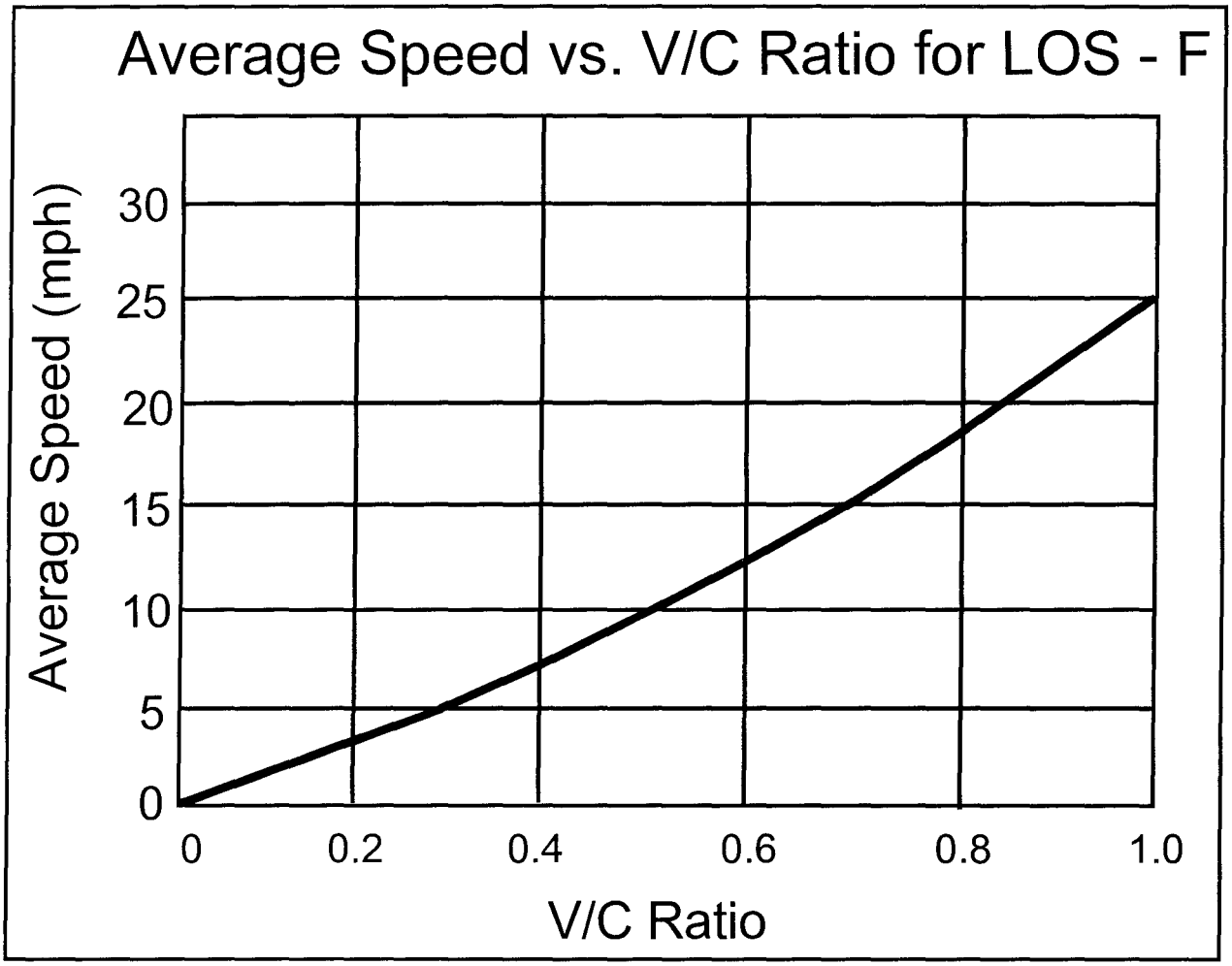



**Figure 3.** V/C Ratio versus Average Queue Speed (Source: NCHRP 133).

$V = V_Q$ = Capacity in Work Zone

$C = C_Q$ = Upstream Capacity

# Problem No. 3

Compute the following user costs associated with the work zone.

| Cost Component | Veh. Class | Number Vehicles | Added VOC | Added Time (Hrs/Veh.) | Value of Time[4] ($/Veh. Hr) | Cost ($) | % |
|---|---|---|---|---|---|---|---|
| ❶WZ Speed Change Delay (55-35-55) | Auto | | | _____/1000 [1,3] | | | |
| | SU | | | _____/1000 [1,3] | | | |
| | Combo | | | _____/1000 [1,3] | | | |
| ❷WZ Speed Change VOC (55-35-55) | Auto | | _____/1000 [1,2] | | | | |
| | SU | | _____/1000 [1,2] | | | | |
| | Combo | | _____/1000 [1,2] | | | | |
| ❸WZ Reduced Speed Delay (35 vs. 55) | Auto | | | _____[5] | | | |
| | SU | | | _____[5] | | | |
| | Combo | | | _____[5] | | | |
| ❹Queue Stopping Delay (55-0-55) | Auto | | | _____/1000 [1,3] | | | |
| | SU | | | _____/1000 [1,3] | | | |
| | Combo | | | _____/1000 [1,3] | | | |
| ❺Queue Stopping VOC (55-0-55) | Auto | | _____/1000 [1,2] | | | | |
| | SU | | _____/1000 [1,2] | | | | |
| | Combo | | _____/1000 [1,2] | | | | |
| ❻Queue Added Travel Time Delay (Queue Speed vs 55) | Auto | | | _____[6] | | | |
| | SU | | | _____[6] | | | |
| | Combo | | | _____[6] | | | |
| ❼Queue Idle VOC | Auto | | _____[7] | _____[6] | | | |
| | SU | | _____[7] | _____[6] | | | |
| | Combo | | _____[7] | _____[6] | | | |
| **Total Work Zone User Cost >>>>>** | | | | | | | |

***Notes:***

1. See Table 2 Page 3.9 for added time and vehicle running cost.
2. Speed change VOC typically given as $/1000 Veh.
3. Speed change delay typically given as Hr/1000 Veh.
4. See Table 3 Page 3.9 for recommended values of time.
5. See Problem No.2 Page 3.6 Answer Ⓐ
6. See Problem No. 2. Page 3.6 Answer Ⓑ
7. See bottom of Table 2 on Page 3.9 for Idle cost rates. Note Idling cost units $/Veh.-Hr.

**Table 2.** Added Time and Vehicle Running Cost / 1000 Stops and Idling Costs (August 1996).

| Initial Speed (mph) | Added Time (Hr / 1000 Stops) (Excludes Idling Time) | | | Added Cost ($/1000 Stops) (Excludes Idling Time) | | |
|---|---|---|---|---|---|---|
| | Pass. Cars | Trucks | | Pass. Car | Trucks | |
| | | Single | Combination | | Single | Combination |
| 5 | 1.02 | 0.73 | 1.10 | 2.70 | 9.25 | 33.62 |
| 10 | 1.51 | 1.47 | 2.27 | 8.83 | 20.72 | 77.49 |
| 15 | 2.00 | 2.20 | 3.48 | 15.16 | 33.89 | 129.97 |
| 20 | 2.49 | 2.93 | 4.76 | 21.74 | 48.40 | 190.06 |
| 25 | 2.98 | 3.67 | 6.10 | 28.67 | 63.97 | 256.54 |
| 30 | 3.46 | 4.40 | 7.56 | 36.10 | 80.23 | 328.21 |
| 35 | 3.94 | 5.13 | 9.19 | 44.06 | 96.88 | 403.84 |
| 40 | 4.42 | 5.87 | 11.09 | 52.70 | 113.97 | 482.21 |
| 45 | 4.90 | 6.60 | 13.39 | 62.07 | 130.08 | 562.14 |
| 50 | 5.37 | 7.33 | 16.37 | 72.31 | 145.96 | 642.41 |
| 55 | 5.84 | 8.07 | 20.72 | 83.47 | 160.89 | 721.77 |
| 60 | 6.31 | 8.80 | 27.94 | 95.70 | 178.98 | 798.99 |
| 65 | 6.78 | 9.53 | NA | 109.02 | 195.84 | NA |
| 70 | 7.25 | NA | NA | 123.61 | NA | NA |
| 75 | 7.71 | NA | NA | 139.53 | NA | NA |
| 80 | 8.17 | NA | NA | 156.85 | NA | NA |
| Idling Cost ($ / vehicle-hour) | | | | 0.6927 | 0.7681 | 0.8248 |

**Table 3.** Recommended Value of Time (August 1996).

| Vehicles Class | $ / Vehicle hour | |
|---|---|---|
| | Value | Range |
| Passenger | 11.58 | 10 – 13 |
| Single Unit | 18.54 | 17 – 19 |
| Combination | 22.31 | 21 – 24 |

# Class Exercise No. 4
# Life Cycle Cost Analysis

A State highway agency is conducting a Life Cycle Cost Analysis of a 6-lane facility (3 lanes per direction). The current directional AADT is 40,000 vehicles per day. The State is considering two alternatives for the initial construction and rehabilitation strategy for one direction. Planned work zones will be in place 24 hours per day during which time the facility is reduced to 2 lanes of operation. Performance life ranges for the two alternative strategies are shown in Table 1.

***Compute the total Net Present Value (NPV) for each alternative.*** Use a 35 year analysis period. Include in your analysis the effect of salvage value, if applicable. Construction costs are directly related to the number of days allowed for initial construction and rehabilitation activities as shown in Figures 1 - 4. Use Table 2 to summarize your selected input values. Real opportunity cost of money to the State highway agency is 4%. The SHA estimates the value of time to be $10 per hour. Routine reactive maintenance cost differences between alternatives are insignificant. Use the formula provided to calculate net present value. If needed use Table 3 for the appropriate discount factor. Use Table 4 to determine the daily cost of delay. Use Table 5 as a worksheet.

**Table 1.** Performance life ranges.

| | Alternative – A | | | | Alternative – B | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | | Rehabs. | | Initial | | Rehabs. | |
| | Low | High | Low | High | Low | High | Low | High |
| Performance (years) | 16 | 24 | 8 | 12 | 10 | 16 | 6 | 8 |

**Table 2.** Selected input values.

| | Alternative – A | | | Alternative – B | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Rehabs. | | | Rehabs | | | |
| | Initial | 1 | 2 | Initial | 1 | 2 | 3 | 4 |
| Performance (years) | | | | | | | | |
| ❶Construction Days[1] | | | | | | | | |
| ❷Agency Cost[2] ($) | | | | | | | | |
| ❸Daily Delay Cost[3] ($) | | | | | | | | |
| ❹User Cost $ (❶ x ❸) | | | | | | | | |

*Notes:* [1,2] See Figures 1.4

[3] See Table 4 Page 4.5

**Table 3.** Discount factors.

| Year | Discount Rate | | | | |
|---|---|---|---|---|---|
| n | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 0 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

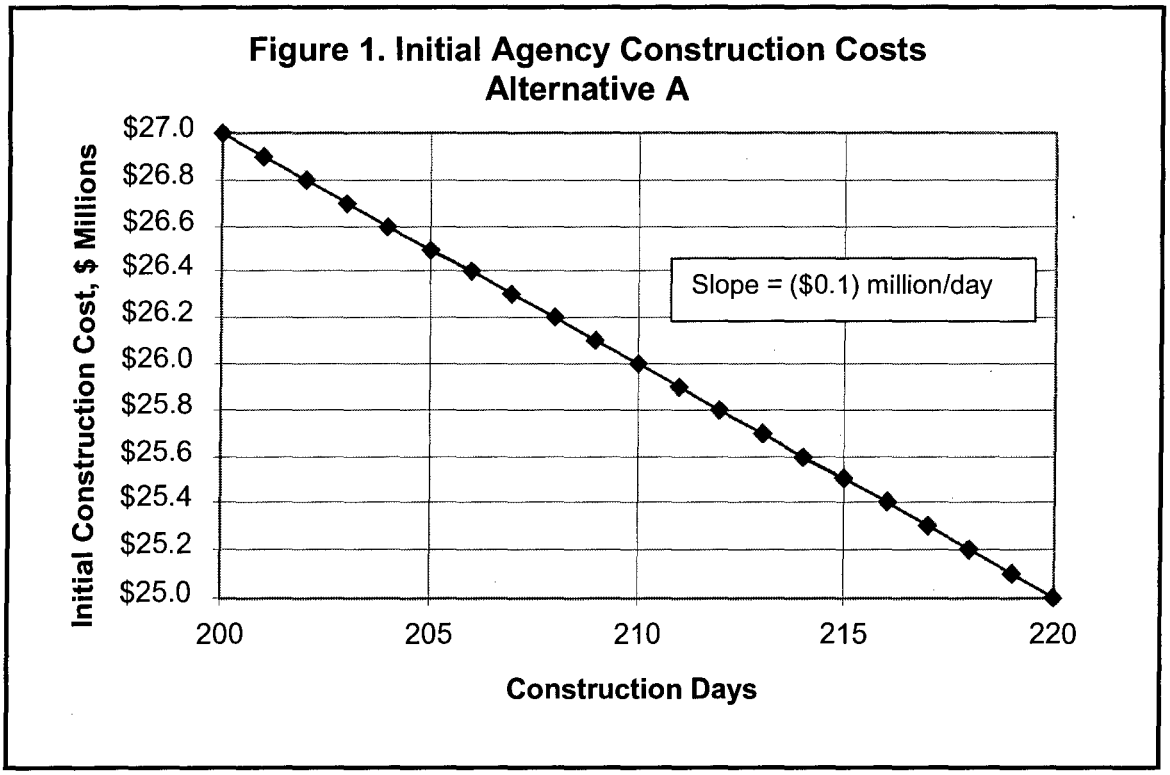


Figure 1. Initial Agency Construction Costs
Alternative A
Initial Construction Cost, $ Millions
$27.0
$26.8
$26.6
$26.4
$26.2
$26.0
$25.8
$25.6
$25.4
$25.2
$25.0
Slope = ($0.1) million/day
200
205
210
215
220
Construction Days

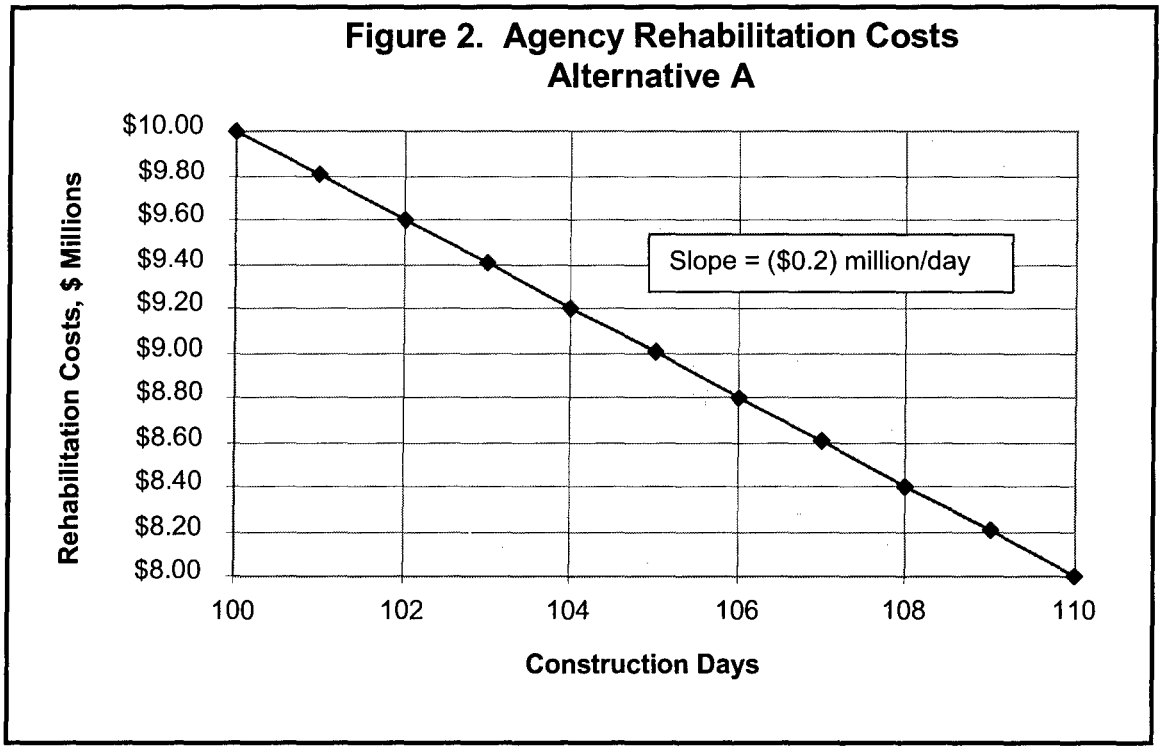


Figure 2. Agency Rehabilitation Costs
Alternative A
Rehabilitation Costs, $ Millions
$10.00
$9.80
$9.60
$9.40
$9.20
$9.00
$8.80
$8.60
$8.40
$8.20
$8.00
Slope = ($0.2) million/day
100
102
104
106
108
110
Construction Days

**Figure 3. Initial Agency Construction Costs - Alternative B**

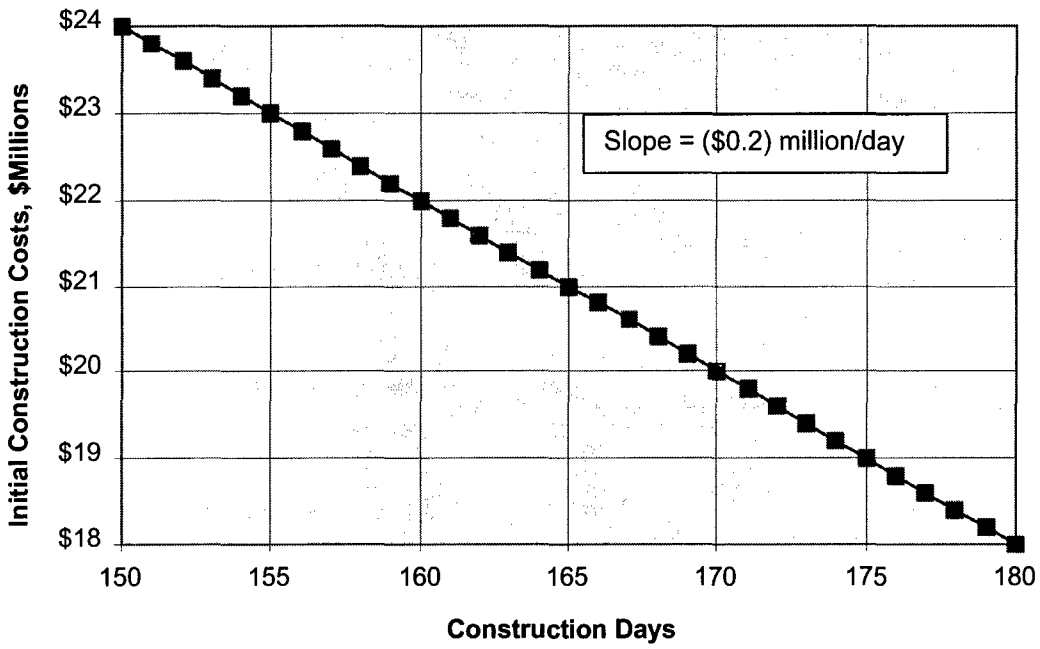
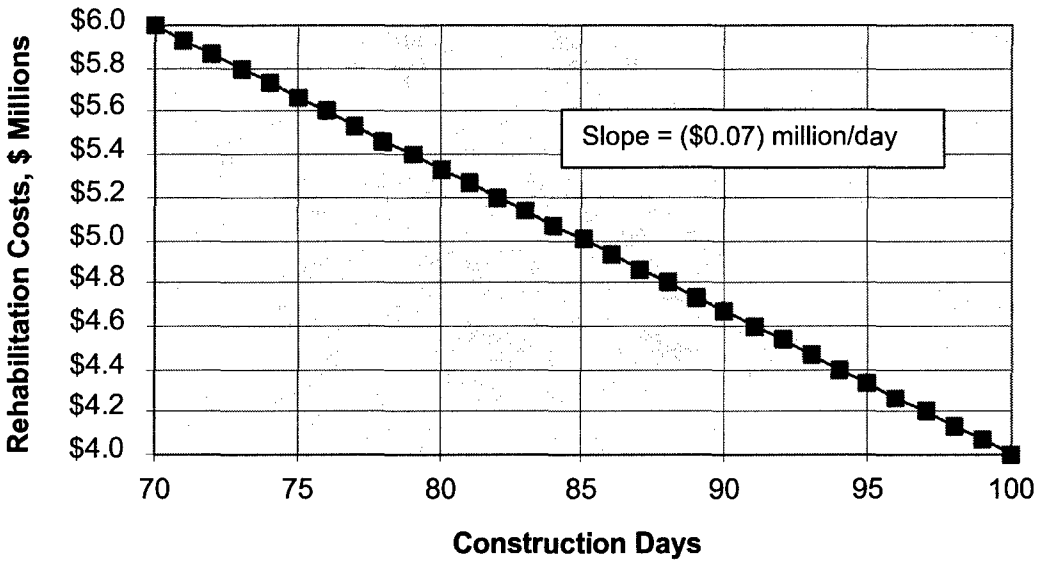



**Figure 4. Agency Rehabilitation Costs Alternative - B**



## Table 4. Daily cost of delay.

| | | | | |
|---|---|---|---|---|
| | Value Time | $ 10.00 | per hour | |
| | Directional AADT(initial) | 40000 | vpd | |
| | Traffic Growth Rate | 3 | percent | |
| | Delay Per Veh. Growth Rate | 10 | percent | |
| Year | AADT | Delay/Veh. min | Daily Delay hours | Daily Cost |
| 0 | 40000 | 5.0 | 3333 | $ 33,333 |
| 1 | 41200 | 5.5 | 3777 | $ 37,767 |
| 2 | 42436 | 6.1 | 4279 | $ 42,790 |
| 3 | 43709 | 6.7 | 4848 | $ 48,481 |
| 4 | 45020 | 7.3 | 5493 | $ 54,929 |
| 5 | 46371 | 8.1 | 6223 | $ 62,234 |
| 6 | 47762 | 8.9 | 7051 | $ 70,511 |
| 7 | 49195 | 9.7 | 7989 | $ 79,889 |
| 8 | 50671 | 10.7 | 9051 | $ 90,514 |
| 9 | 52191 | 11.8 | 10255 | $ 102,553 |
| 10 | 53757 | 13.0 | 11619 | $ 116,192 |
| 11 | 55369 | 14.3 | 13165 | $ 131,646 |
| 12 | 57030 | 15.7 | 14915 | $ 149,155 |
| 13 | 58741 | 17.3 | 16899 | $ 168,993 |
| 14 | 60504 | 19.0 | 19147 | $ 191,469 |
| 15 | 62319 | 20.9 | 21693 | $ 216,934 |
| 16 | 64188 | 23.0 | 24579 | $ 245,786 |
| 17 | 66114 | 25.3 | 27848 | $ 278,476 |
| 18 | 68097 | 27.8 | 31551 | $ 315,513 |
| 19 | 70140 | 30.6 | 35748 | $ 357,476 |
| 20 | 72244 | 33.6 | 40502 | $ 405,020 |
| 21 | 74412 | 37.0 | 45889 | $ 458,888 |
| 22 | 76644 | 40.7 | 51992 | $ 519,920 |
| 23 | 78943 | 44.8 | 58907 | $ 589,070 |
| 24 | 81312 | 49.2 | 66742 | $ 667,416 |
| 25 | 83751 | 54.2 | 75618 | $ 756,182 |
| 26 | 86264 | 59.6 | 85675 | $ 856,755 |
| 27 | 88852 | 65.5 | 97070 | $ 970,703 |
| 28 | 91517 | 72.1 | 109981 | $ 1,099,806 |
| 29 | 94263 | 79.3 | 124608 | $ 1,246,081 |
| 30 | 97090 | 87.2 | 141181 | $ 1,411,809 |
| 31 | 100003 | 96.0 | 159958 | $ 1,599,580 |
| 32 | 103003 | 105.6 | 181232 | $ 1,812,324 |
| 33 | 106093 | 116.1 | 205336 | $ 2,053,363 |
| 34 | 109276 | 127.7 | 232646 | $ 2,326,460 |
| 35 | 112554 | 140.5 | 263588 | $ 2,635,880 |
| 36 | 115931 | 154.6 | 298645 | $ 2,986,452 |
| 37 | 119409 | 170.0 | 338365 | $ 3,383,650 |
| 38 | 122991 | 187.0 | 383368 | $ 3,833,675 |
| 39 | 126681 | 205.7 | 434355 | $ 4,343,554 |
| 40 | 130482 | 226.3 | 492125 | $ 4,921,247 |

***Note:***
Values shown are for illustrative purposes only.

**Table 5.** NPV Worksheet.

| | Year | | | | | |
|---|---|---|---|---|---|---|
| **Alternative - A** | 0 | | | | | |
| Agency Cost (Constant $) | | | | | | |
| Present Worth Factor | | | | | | |
| Agency Cost (Present Worth) | | | | | | |
| Total NPV (Agency Cost) | | | | | | |
| | | | | | | |
| User Cost (Constant $) | | | | | | |
| Present Worth Factor | | | | | | |
| User Cost (Present Worth) | | | | | | |
| Total NPV (User Cost) | | | | | | |
| | | | | | | |
| Grand Total NPV (all costs) | | | | | | |

| | Year | | | | | |
|---|---|---|---|---|---|---|
| **Alternative - B** | 0 | | | | | |
| Agency Cost (Constant $) | | | | | | |
| Present Worth Factor | | | | | | |
| Agency Cost (Present Worth) | | | | | | |
| Total NPV (Agency Cost) | | | | | | |
| | | | | | | |
| User Cost (Constant $) | | | | | | |
| Present Worth Factor | | | | | | |
| User Cost (Present Worth) | | | | | | |
| Total NPV (User Cost) | | | | | | |
| | | | | | | |
| Grand Total NPV (all costs) | | | | | | |

# Class Exercise No. 1
# Net Present Value (Solution)

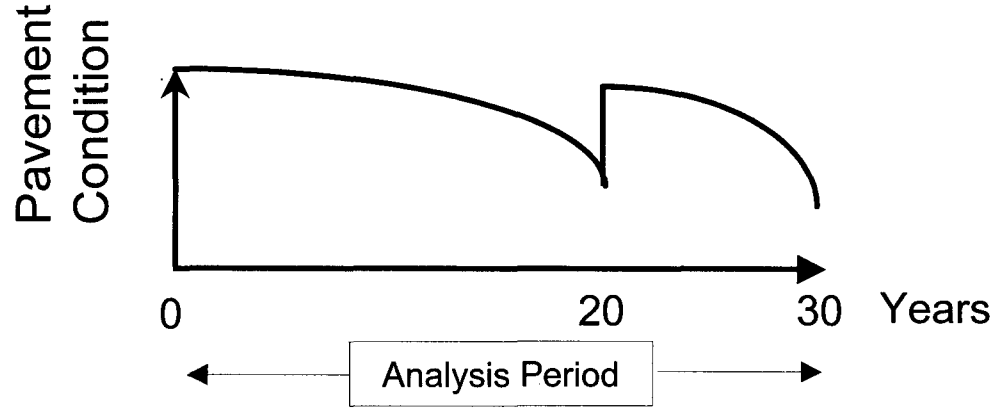
Compute the total Net Present Value (NPV) for the following Alternative.

| | Initial Constr. | Rehab. |
|---|---|---|
| Design Period, (yrs) | 20 | 10 |
| Agency Cost ($ Millions) | 26 | 9 |
| Construction Period (days) | 210 | 105 |

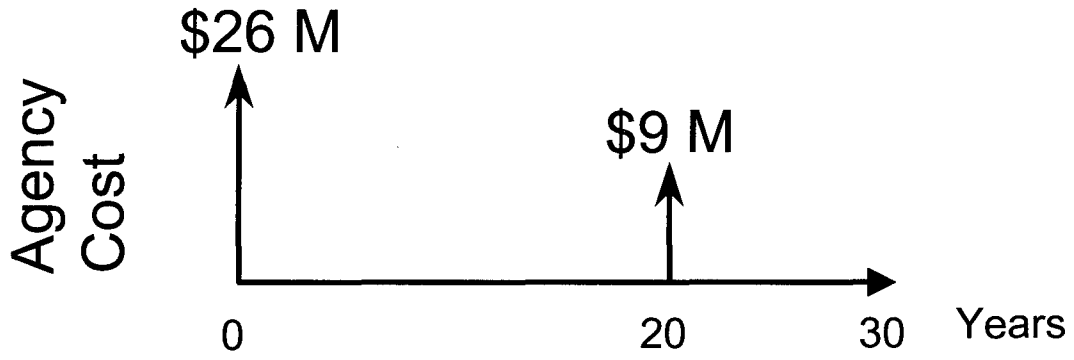
Assume the following:

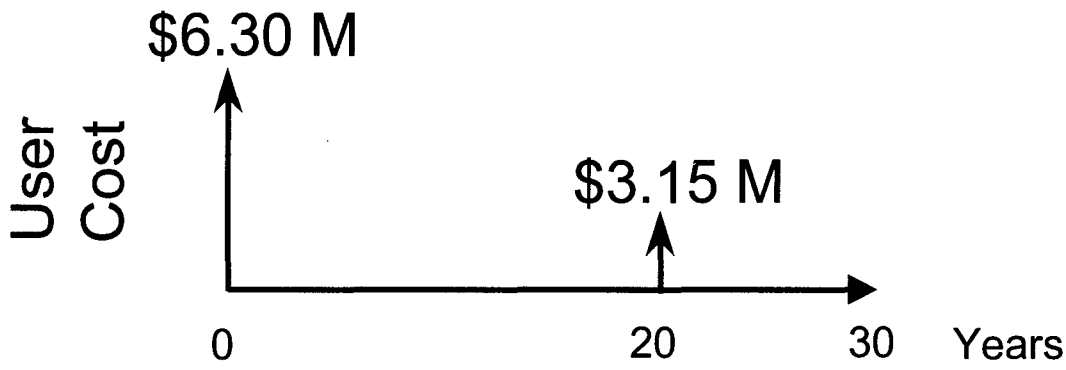
| | |
|---|---|
| Analysis Period (yrs) | 30 |
| Daily Delay (Hours) | 3000 |
| Routine Maintenance | Insignificant |
| Discount Rate, % | 4 |
| Value of Time ($/hr) | 10 |

# Performance Curve




# Expenditure Streams



# User Cost Calculations

User Cost = Construction Days x Daily Delay x Value of Time

## Initial Construction

User Cost = 210 days x 3000 hrs/day x $10 / hr.

= $6.30 Million

## Rehabilitation

User Cost = 105 days x 3000 hrs/day x $10 / hr.

= $3.15 Million

$$NPV = InitialCost + \sum_{k=1}^{N} FutureCost\left[\frac{1}{(1+i)^{n_k}}\right]$$

Note: Quantity in brackets is present value factor from page 1.5.

# Agency Cost

NPV = $26 + $9 (0.4564) = $30.12 M

# User Cost

NPV = $6.3 + $3.15 (0.4564) = $7.74 M

# Present Value Factors

| Year n | Discount Rate, (i) | | | | |
|---|---|---|---|---|---|
| | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

# Class Exercise No. 2
# Net Present Value (Solution)

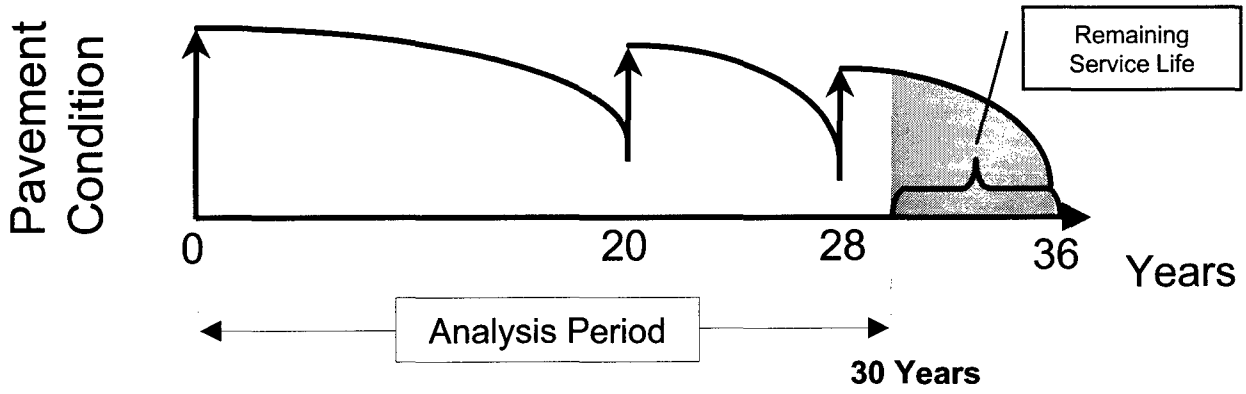
Compute the total Net Present Value (NPV) for the following Alternative.

| | Initial Constr. | Rehab. |
|---|---|---|
| Design Period, (yrs) | 20 | 8 |
| Agency Cost ($ Millions) | 30 | 9 |
| Construction Period (days) | 200 | 80 |

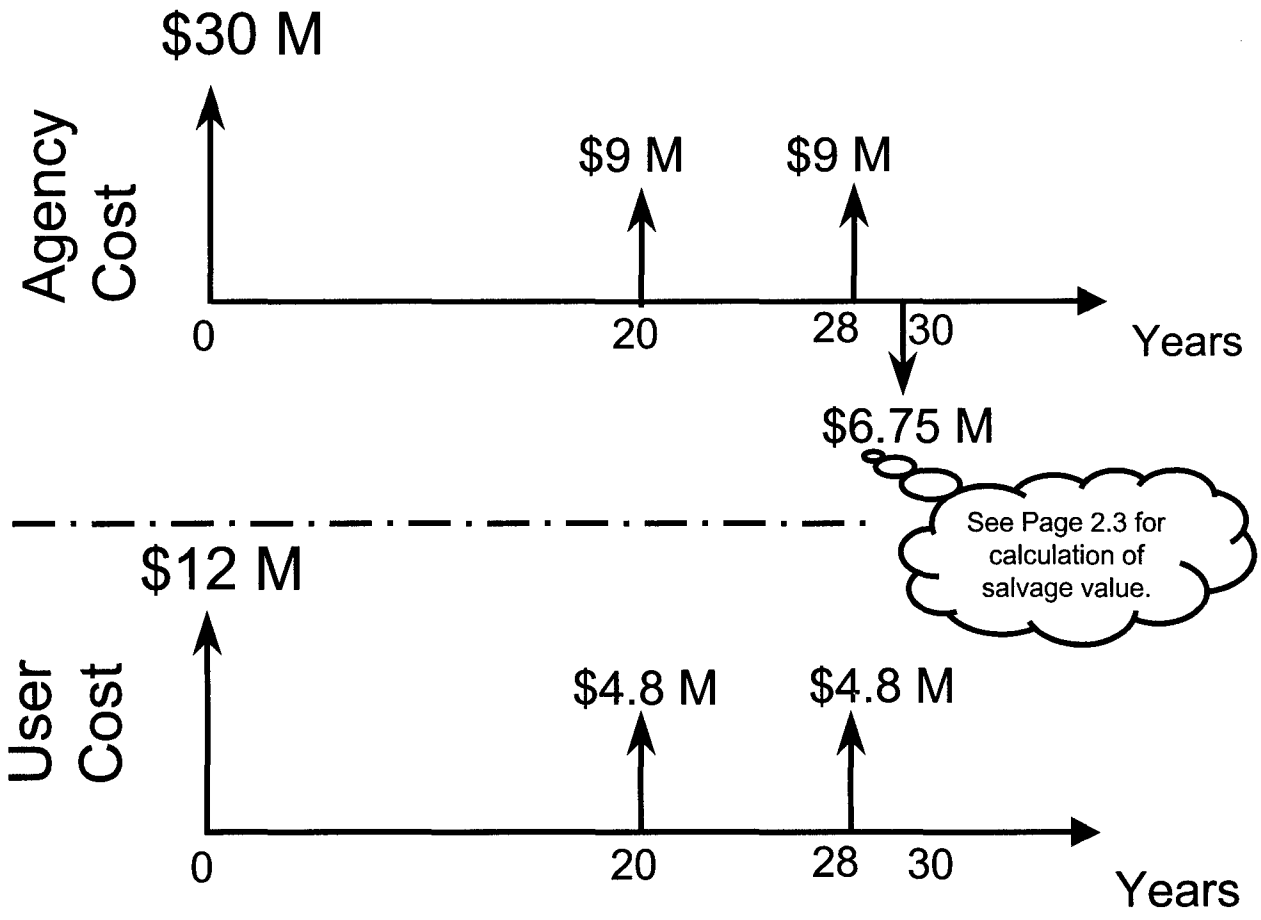
Assume the following:

| | |
|---|---|
| Analysis Period (yrs) | 30 |
| Daily Delay (Hours) | 4000 |
| Routine Maintenance | Insignificant |
| Discount Rate, % | 4 |
| Value of Time ($/hr) | 15 |

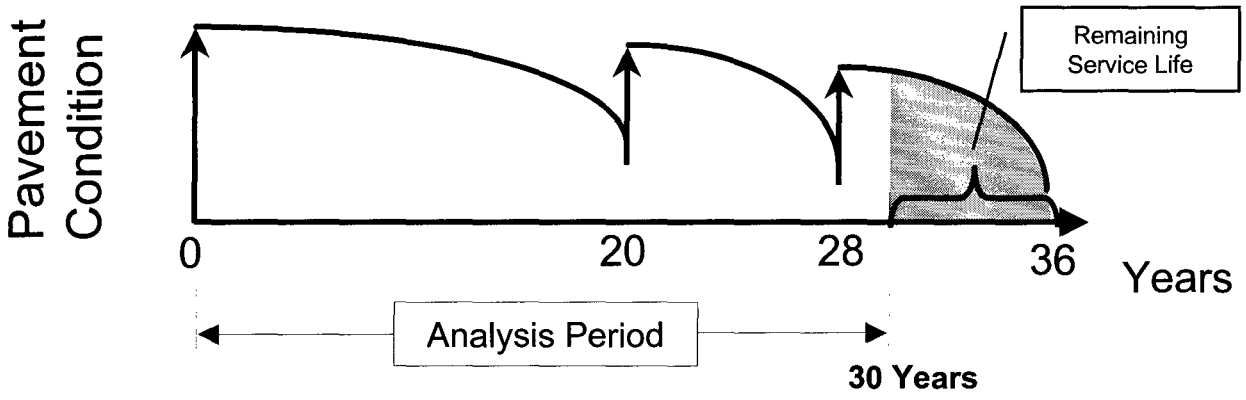
# Performance Curve

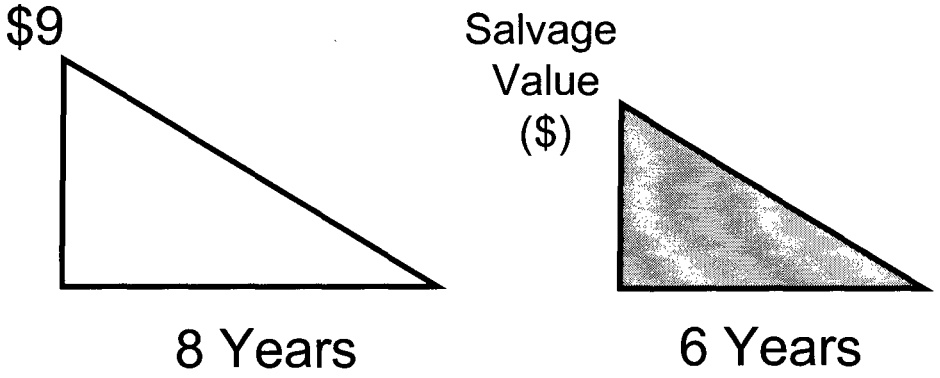



# Expenditure Streams



# Salvage Value Calculation




Salvage Value = (9 / 8) * 6 = $ 6.75

# User Cost Calculations

User Cost = Construction Days x Daily Delay x Value of Time

## Initial Construction

User Cost = 200 days x 4000 hrs/day x $15 / hr.

= $12 Million

## Rehabilitation

User Cost = 80 days x 4000 hrs/day x $15 / hr.

= $4.8 Million

$$NPV = InitialCost + \sum_{k=1}^{N} FutureCost\left[\frac{1}{(1+i)^{n_k}}\right]$$

Note: Quantity in brackets is present value factor from page 2.6.

# Agency Cost

NPV = \$30 + \$9(0.4564) + \$9 (0.3335) - \$6.75 (0.3083)
= \$35.03 M

# User Cost

NPV = \$12 + \$4.8(0.4564) + \$4.8 (0.3335)
= \$15.79 M

# Present Value Factors

| Year n | Discount Rate, (i) | | | | |
|---|---|---|---|---|---|
| | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

# Class Exercise No. 3 (Solution)
# Work Zone User Cost

## Problem No. 1

Using the data from the 24 hour capacity analysis shown in Table 1 quantify the traffic affected for each of the following user cost components for the duration of the project.

**❶ WZ Speed Change Delay (Free Flow)**
**55 ➡ 35 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 339,647 |
| 6% Single Unit | 22,643 |
| 4% Combination | 15,095 |

**❷ WZ Speed Change VOC (Free Flow)**
**55 ➡ 35 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 339,647 |
| 6% Single Unit | 22,643 |
| 4% Combination | 15,095 |

**❸ Reduced Speed Delay Base Case (Free Flow)**
**35 vs 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 3,462,750 |
| 6% Single Unit | 230,850 |
| 4% Combination | 153,900 |

***Note:*** *Problem No. 1 continued on next page.*

# Problem No. 1 Continued

**❹ Queue Stopping Delay (Forced Flow)**
**55 ➡ 0 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 3,123,103 |
| 6% Single Unit | 208,207 |
| 4% Combination | 138,805 |

**❺ Queue Stopping VOC (Forced Flow)**
**55 ➡ 0 ➡ 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 3,123,103 |
| 6% Single Unit | 208,207 |
| 4% Combination | 138,805 |

**❻ Queue Added Travel Delay**
**Queue Speed vs. 55 mph**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 3,123,103 |
| 6% Single Unit | 208,207 |
| 4% Combination | 138,805 |

**❼ Queue Idle VOC**

| Vehicle Class | Eastbound Number of Vehicles |
|---|---|
| 90% Auto | 3,123,103 |
| 6% Single Unit | 208,207 |
| 4% Combination | 138,805 |

# Problem No. 2

Compute the reduced speed delay to traverse the work zone.

| | | Work Zone Length | Time |
|---|---|---|---|
| **Work Zone Speed** | 35 mph | 7 mi. | 0.20000 hrs. |
| **Upstream Speed** | 55 mph | 7 mi. | 0.12727 hrs. |
| Ⓐ **Increased Time to Traverse the Work Zone:** | | | 0.07273 hrs. |

Compute the reduced speed delay to traverse the queue.

| Computation Step | | Value |
|---|---|---|
| ❶ Maximum number of queued vehicles | | 4,721 vehicles |
| Queue Volume ($V_Q$) "Capacity of Work Zone" | | 2,800 vehicles |
| Queue Capacity ($C_Q$) "Upstream Capacity" | | 6,300 vehicles |
| $V_Q/C_Q$ | | 2,800/6,300 0.44 |
| Queue Speed ($S_Q$) *(See Figure 3 Page 3.4)* | | 8 mph |
| ❷ Work Zone Density ($V_Q/S_Q$) | | 2,800 / 8 = 350 vpm |
| Upstream Volume ($V_U$) "Demand at Max. No. Queued Vehicles" | | 3,027 vehicles |
| Upstream Speed ($S_U$) | | 55 mph |
| ❸ Upstream Density ($V_U/S_U$) | | 3,027 / 55 = 55 vpm |
| △ Density (❷ - ❸) | | 295 vpm |
| ❹ Maximum Queue Length (❶ / △ Density) | | 4,721 / 295 = 16.0 miles |
| ❺ Average Queue Length (❹ / 2) | | 16.0 / 2 = 8.0 miles |
| Queue Travel Time | ❻ ❺ /Queue Speed ($S_Q$) (hrs) | 8 / 8 = 1 Hour |
| | ❼ ❺ /Upstream Speed ($S_U$) (hrs) | 8 / 55 = 0.1455 Hour |
| Ⓑ Queue Delay (hrs) (❻ - ❼) | | 0.8548 Hour |

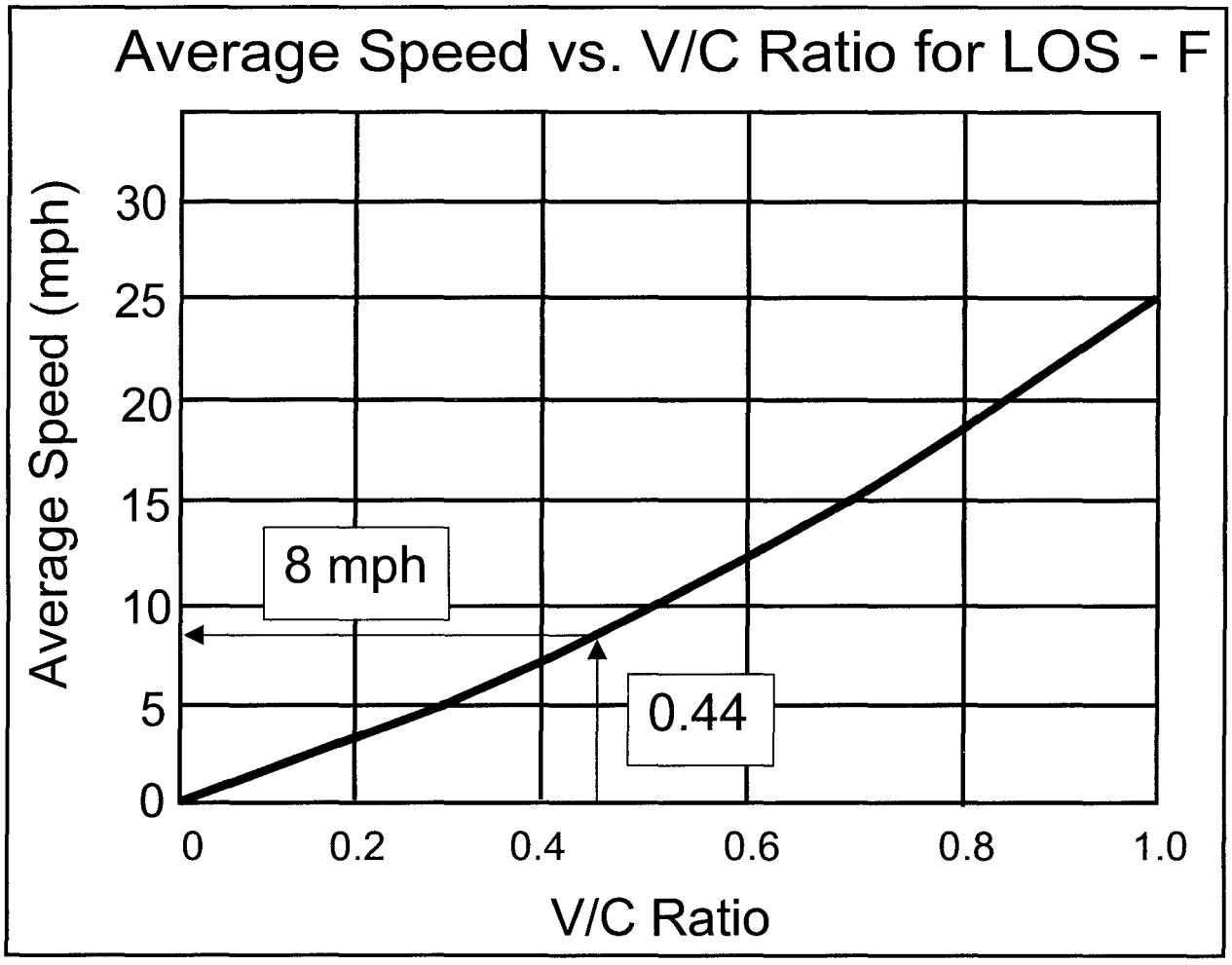



**Figure 4.** V/C Ratio versus Average Queue Speed (Source: NCHRP 133).

***Note:***

V = $V_Q$ = Capacity in Work Zone

C = $C_Q$ = Upstream Capacity

# Problem No. 3

Compute the following user costs associated with the work zone.

| Cost Component | Veh. Class | Number Vehicles | Added VOC | Added Time (Hrs/Veh.) | Value of Time[4] ($/Veh. Hr) | Cost ($) | % |
|---|---|---|---|---|---|---|---|
| ❶WZ Speed Change Delay (55-35-55) | Auto | 339,647 | | 1.90 / 1000 [1,3] | 11.58 | 7,473 | 0.02 |
| | SU | 22,643 | | 2.94 / 1000 [1,3] | 18.54 | 1,234 | 0.00 |
| | Combo | 15,095 | | 11.53 / 1000 [1,3] | 22.31 | 3,883 | 0.01 |
| ❷WZ Speed Change VOC (55-35-55) | Auto | 339,647 | 39.42 / 1000 [1,2] | | | 13,385 | 0.03 |
| | SU | 22,643 | 64.01 / 1000 [1,2] | | | 1,449 | 0.00 |
| | Combo | 15,095 | 317.93 / 1000 [1,2] | | | 4,799 | 0.01 |
| ❸WZ Reduced Speed Delay (35 vs. 55) | Auto | 3,462,750 | | 0.0727 [5] | 11.58 | 2,916,265 | 6.76 |
| | SU | 230,850 | | 0.0727 [5] | 18.54 | 311,270 | 0.72 |
| | Combo | 153,900 | | 0.0727 [5] | 22.31 | 249,710 | 0.58 |
| ❹Queue Stopping Delay (55-0-55) | Auto | 3,123,103 | | 5.84 / 1000 [1,3] | 11.58 | 211,207 | 0.49 |
| | SU | 208,207 | | 8.07 / 1000 [1,3] | 18.54 | 31,151 | 0.07 |
| | Combo | 138,805 | | 20.72 / 1000 [1,3] | 22.31 | 64,164 | 0.15 |
| ❺Queue Stopping VOC (55-0-55) | Auto | 3,123,103 | 83.47 / 1000 [1,2] | | | 260,685 | 0.60 |
| | SU | 208,207 | 160.89 / 1000 [1,2] | | | 33,498 | 0.08 |
| | Combo | 138,805 | 721.77 / 1000 [1,2] | | | 100,185 | 0.23 |
| ❻Queue Added Travel Time Delay (Queue Speed vs 55) | Auto | 3,123,103 | | 0.8548 [6] | 11.58 | 30,915,530 | 71.64 |
| | SU | 208,207 | | 0.8548 [6] | 18.54 | 3,299,792 | 7.65 |
| | Combo | 138,805 | | 0.8548 [6] | 22.31 | 2,647,190 | 6.13 |
| ❼Queue Idle VOC | Auto | 3,123,103 | 0.6927 [7] | 0.8548 [6] | | 1,849,325 | 4.29 |
| | SU | 208,207 | 0.7681 [7] | 0.8548 [6] | | 136,708 | 0.32 |
| | Combo | 138,805 | 0.8248 [7] | 0.8548 [6] | | 97,867 | 0.23 |
| | | | | | Total Work Zone User Cost >>>>> | 43,156,773 | |

***Notes:***

1. See Table 2 Page 3.9 for added time and vehicle running cost.
2. Speed change VOC typically given as $/1000 Veh.
3. Speed change delay typically given as Hr/1000 Veh.
4. See Table 3 Page 3.9 for recommended values of time.
5. See Problem No.2 Page 3.6 Answer Ⓐ
6. See Problem No. 2. Page 3.6 Answer Ⓑ
7. See bottom of Table 2 on Page 3.9 for Idle cost rates. Note Idling cost units $/Veh.-Hr.

**Table 2.** Added Time and Vehicle Running Cost / 1000 Stops and Idling Costs (August 1996).

| Initial Speed (mph) | Added Time (Hr / 1000 Stops) (Excludes Idling Time) | | | Added Cost ($/1000 Stops) (Excludes Idling Time) | | |
|---|---|---|---|---|---|---|
| | Pass. Cars | Trucks | | Pass. Car | Trucks | |
| | | Single | Combination | | Single | Combination |
| 5 | 1.02 | 0.73 | 1.10 | 2.70 | 9.25 | 33.62 |
| 10 | 1.51 | 1.47 | 2.27 | 8.83 | 20.72 | 77.49 |
| 15 | 2.00 | 2.20 | 3.48 | 15.16 | 33.89 | 129.97 |
| 20 | 2.49 | 2.93 | 4.76 | 21.74 | 48.40 | 190.06 |
| 25 | 2.98 | 3.67 | 6.10 | 28.67 | 63.97 | 256.54 |
| 30 | 3.46 | 4.40 | 7.56 | 36.10 | 80.23 | 328.21 |
| 35 | 3.94 | 5.13 | 9.19 | 44.06 | 96.88 | 403.84 |
| 40 | 4.42 | 5.87 | 11.09 | 52.70 | 113.97 | 482.21 |
| 45 | 4.90 | 6.60 | 13.39 | 62.07 | 130.08 | 562.14 |
| 50 | 5.37 | 7.33 | 16.37 | 72.31 | 145.96 | 642.41 |
| 55 | 5.84 | 8.07 | 20.72 | 83.47 | 160.89 | 721.77 |
| 60 | 6.31 | 8.80 | 27.94 | 95.70 | 178.98 | 798.99 |
| 65 | 6.78 | 9.53 | NA | 109.02 | 195.84 | NA |
| 70 | 7.25 | NA | NA | 123.61 | NA | NA |
| 75 | 7.71 | NA | NA | 139.53 | NA | NA |
| 80 | 8.17 | NA | NA | 156.85 | NA | NA |
| Idling Cost ($ / vehicle-hour) | | | | 0.6927 | 0.7681 | 0.8248 |

**Table 3.** Recommended Value of Time (August 1996).

| Vehicles Class | $ / Vehicle hour | |
|---|---|---|
| | Value | Range |
| Passenger | 11.58 | 10 – 13 |
| Single Unit | 18.54 | 17 – 19 |
| Combination | 22.31 | 21 – 24 |

# Class Exercise No. 4 (Solution)
# Life Cycle Cost Analysis

A State highway agency is conducting a Life Cycle Cost Analysis of a 6-lane facility (3 lanes per direction). The current directional AADT is 40,000 vehicles per day. The State is considering two alternatives for the initial construction and rehabilitation strategy for one direction. Planned work zones will be in place 24 hours per day during which time the facility is reduced to 2 lanes of operation. Performance life ranges for the two alternative strategies are shown in Table 1.

***Compute the total Net Present Value (NPV) for each alternative.*** Use a 35 year analysis period. Include in your analysis the effect of salvage value, if applicable. Construction costs are directly related to the number of days allowed for initial construction and rehabilitation activities as shown in Figures 1 - 4. Use Table 2 to summarize your selected input values. Real opportunity cost of money to the State highway agency is 4%. The SHA estimates the value of time to be $10 per hour. Routine reactive maintenance cost differences between alternatives are insignificant. Use the formula provided to calculate net present value. If needed use Table 3 for the appropriate discount factor. Use Table 4 to determine the daily cost of delay. Use Table 5 as a worksheet.

**Table 1.** Performance life ranges.

| | Alternative – A | | | | Alternative – B | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | | Rehabs. | | Initial | | Rehabs. | |
| | Low | High | Low | High | Low | High | Low | High |
| **Performance (years)** | 16 | 24 | 8 | 12 | 10 | 16 | 6 | 8 |

**Table 2.** Selected input values.

| | Alternative – A | | | Alternative – B | | | |
|---|---|---|---|---|---|---|---|
| | | Rehabs. | | | Rehabs | | |
| | Initial | 1 | 2 | Initial | 1 | 2 | 3 |
| **Performance (years)** | 20 | 10 | 10 | 15 | 7 | 7 | 7 |
| **❶Construction Days[1]** | 220 | 100 | 100 | 180 | 70 | 70 | 70 |
| **❷Agency Cost[2] ($)** | 25 M | 10 M | 10 M | 18 M | 6 M | 6 M | 6 M |
| **❸Daily Delay Cost[3] $** | 33,333 | 405,020 | 1411,809 | 33,333 | 216,934 | 519,920 | 1,246,080 |
| **❹User Cost $ (❶ x ❸)** | 7.3 M | 40.5 M | 141.2 M | 6.0 M | 15.18 M | 36.39 M | 87.22 M |

***Notes:*** [1, 2] See Figures 1.4.
[3] See Table 4 Page 4.5.

**Table 3.** Discount Factors.

| Year | Discount Rate | | | | |
|---|---|---|---|---|---|
| **n** | 4.0% | 4.5% | 5.0% | 5.5% | 6.0% |
| 0 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 1 | 0.9615 | 0.9569 | 0.9524 | 0.9479 | 0.9434 |
| 2 | 0.9246 | 0.9157 | 0.9070 | 0.8985 | 0.8900 |
| 3 | 0.8890 | 0.8763 | 0.8638 | 0.8516 | 0.8396 |
| 4 | 0.8548 | 0.8386 | 0.8227 | 0.8072 | 0.7921 |
| 5 | 0.8219 | 0.8025 | 0.7835 | 0.7651 | 0.7473 |
| 6 | 0.7903 | 0.7679 | 0.7462 | 0.7252 | 0.7050 |
| 7 | 0.7599 | 0.7348 | 0.7107 | 0.6874 | 0.6651 |
| 8 | 0.7307 | 0.7032 | 0.6768 | 0.6516 | 0.6274 |
| 9 | 0.7026 | 0.6729 | 0.6446 | 0.6176 | 0.5919 |
| 10 | 0.6756 | 0.6439 | 0.6139 | 0.5854 | 0.5584 |
| 11 | 0.6496 | 0.6162 | 0.5847 | 0.5549 | 0.5268 |
| 12 | 0.6246 | 0.5897 | 0.5568 | 0.5260 | 0.4970 |
| 13 | 0.6006 | 0.5643 | 0.5303 | 0.4986 | 0.4688 |
| 14 | 0.5775 | 0.5400 | 0.5051 | 0.4726 | 0.4423 |
| 15 | 0.5553 | 0.5167 | 0.4810 | 0.4479 | 0.4173 |
| 16 | 0.5339 | 0.4945 | 0.4581 | 0.4246 | 0.3936 |
| 17 | 0.5134 | 0.4732 | 0.4363 | 0.4024 | 0.3714 |
| 18 | 0.4936 | 0.4528 | 0.4155 | 0.3815 | 0.3503 |
| 19 | 0.4746 | 0.4333 | 0.3957 | 0.3616 | 0.3305 |
| 20 | 0.4564 | 0.4146 | 0.3769 | 0.3427 | 0.3118 |
| 21 | 0.4388 | 0.3968 | 0.3589 | 0.3249 | 0.2942 |
| 22 | 0.4220 | 0.3797 | 0.3418 | 0.3079 | 0.2775 |
| 23 | 0.4057 | 0.3634 | 0.3256 | 0.2919 | 0.2618 |
| 24 | 0.3901 | 0.3477 | 0.3101 | 0.2767 | 0.2470 |
| 25 | 0.3751 | 0.3327 | 0.2953 | 0.2622 | 0.2330 |
| 26 | 0.3607 | 0.3184 | 0.2812 | 0.2486 | 0.2198 |
| 27 | 0.3468 | 0.3047 | 0.2678 | 0.2356 | 0.2074 |
| 28 | 0.3335 | 0.2916 | 0.2551 | 0.2233 | 0.1956 |
| 29 | 0.3207 | 0.2790 | 0.2429 | 0.2117 | 0.1846 |
| 30 | 0.3083 | 0.2670 | 0.2314 | 0.2006 | 0.1741 |
| 31 | 0.2965 | 0.2555 | 0.2204 | 0.1902 | 0.1643 |
| 32 | 0.2851 | 0.2445 | 0.2099 | 0.1803 | 0.1550 |
| 33 | 0.2741 | 0.2340 | 0.1999 | 0.1709 | 0.1462 |
| 34 | 0.2636 | 0.2239 | 0.1904 | 0.1620 | 0.1379 |
| 35 | 0.2534 | 0.2143 | 0.1813 | 0.1535 | 0.1301 |

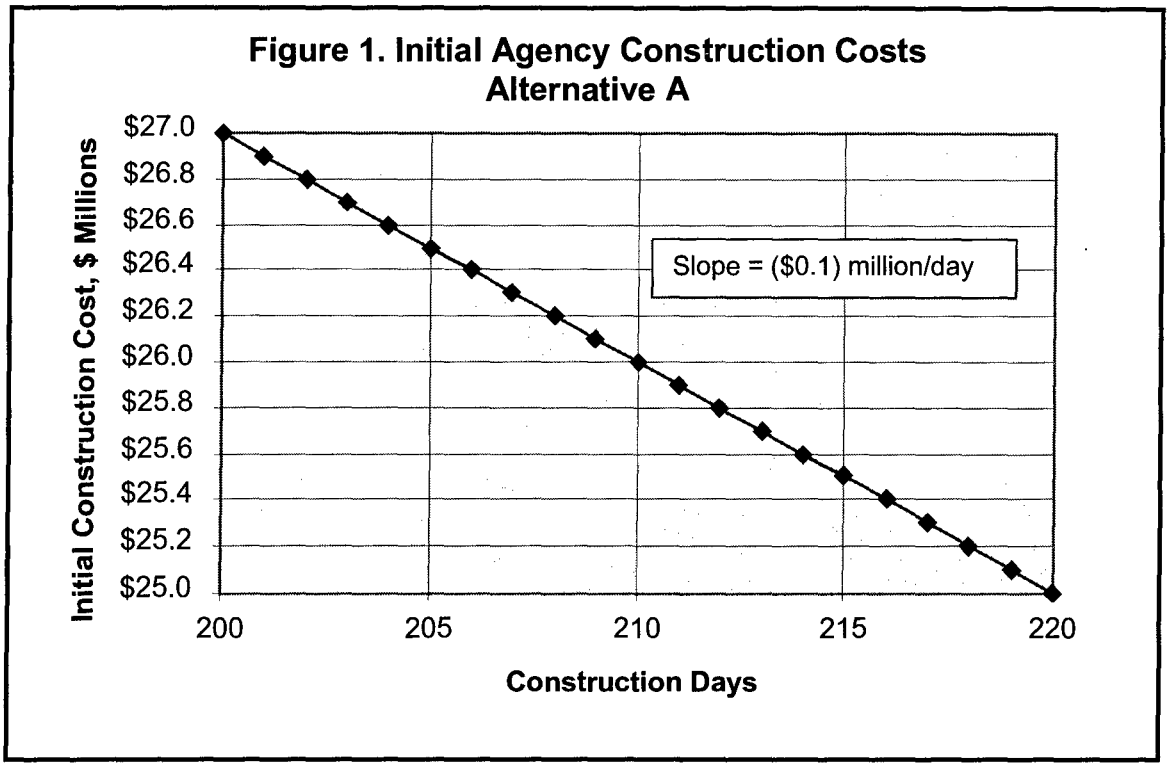


Figure 1. Initial Agency Construction Costs
Alternative A
Initial Construction Cost, $ Millions
$27.0
$26.8
$26.6
$26.4
$26.2
$26.0
$25.8
$25.6
$25.4
$25.2
$25.0
Slope = ($0.1) million/day
200
205
210
215
220
Construction Days

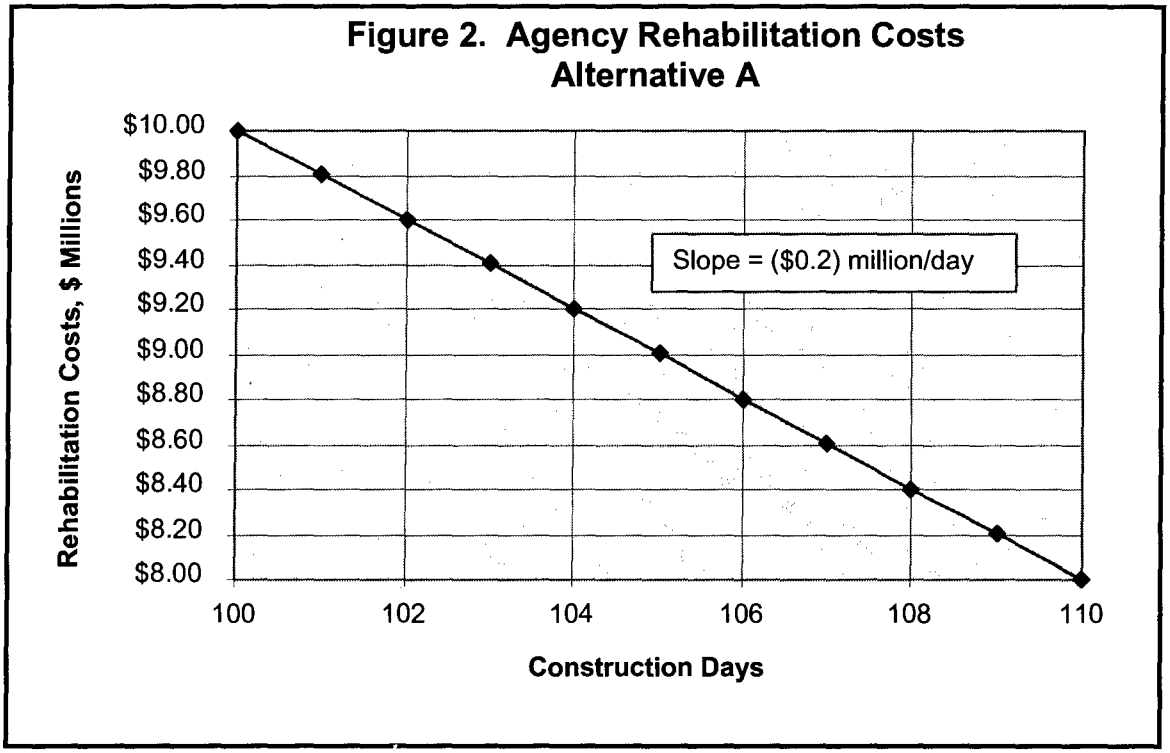


Figure 2. Agency Rehabilitation Costs
Alternative A
Rehabilitation Costs, $ Millions
$10.00
$9.80
$9.60
$9.40
$9.20
$9.00
$8.80
$8.60
$8.40
$8.20
$8.00
Slope = ($0.2) million/day
100
102
104
106
108
110
Construction Days

**Figure 3. Initial Agency Construction Costs - Alternative B**

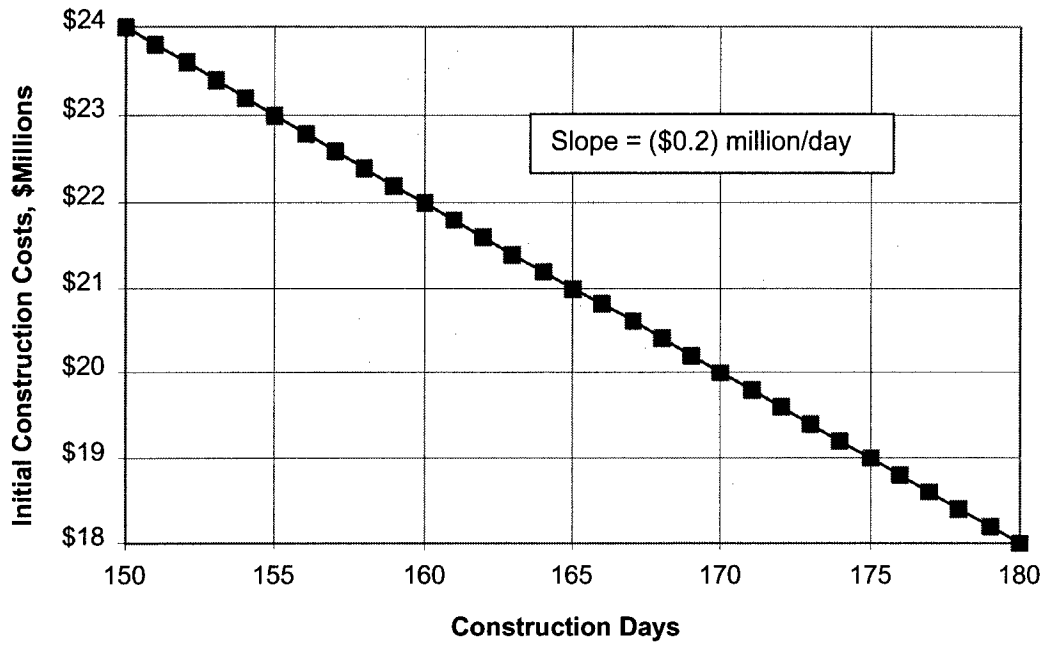



**Figure 4. Agency Rehabilitation Costs Alternative - B**

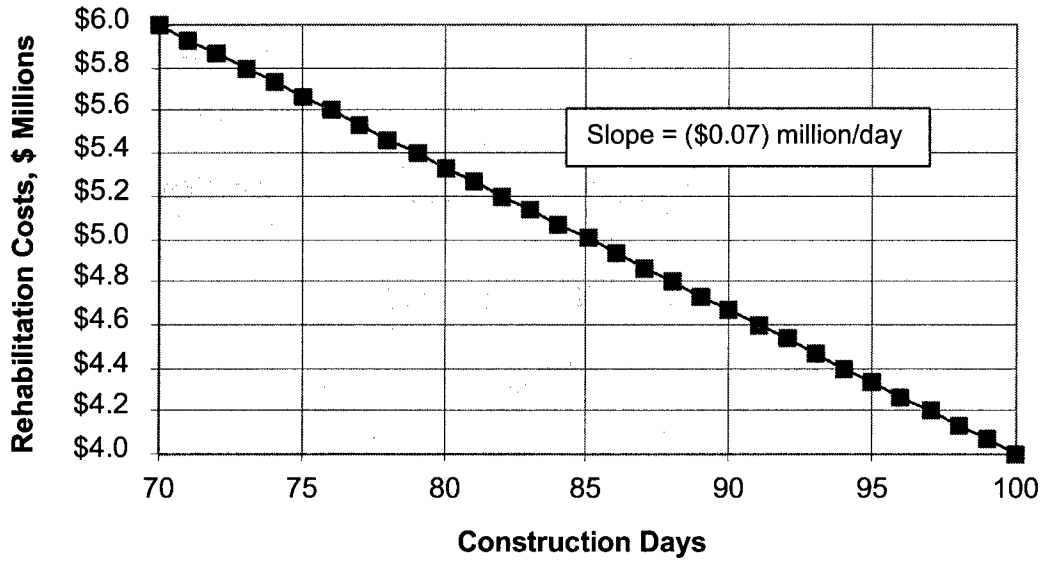


**Table 4.** Daily cost of delay.

| | | | | |
|---|---|---|---|---|
| **Value Time** | $ 10.00 | **per hour** | | |
| **Directional AADT(initial)** | 40000 | **vpd** | | |
| **Traffic Growth Rate** | 3 | **percent** | | |
| **Delay Per Veh. Growth Rate** | 10 | **percent** | | |

| Year | AADT | Delay/Veh. min | Daily Delay hours | Daily Cost |
|---|---|---|---|---|
| 0 | 40000 | 5.0 | 3333 | $ 33,333 |
| 1 | 41200 | 5.5 | 3777 | $ 37,767 |
| 2 | 42436 | 6.1 | 4279 | $ 42,790 |
| 3 | 43709 | 6.7 | 4848 | $ 48,481 |
| 4 | 45020 | 7.3 | 5493 | $ 54,929 |
| 5 | 46371 | 8.1 | 6223 | $ 62,234 |
| 6 | 47762 | 8.9 | 7051 | $ 70,511 |
| 7 | 49195 | 9.7 | 7989 | $ 79,889 |
| 8 | 50671 | 10.7 | 9051 | $ 90,514 |
| 9 | 52191 | 11.8 | 10255 | $ 102,553 |
| 10 | 53757 | 13.0 | 11619 | $ 116,192 |
| 11 | 55369 | 14.3 | 13165 | $ 131,646 |
| 12 | 57030 | 15.7 | 14915 | $ 149,155 |
| 13 | 58741 | 17.3 | 16899 | $ 168,993 |
| 14 | 60504 | 19.0 | 19147 | $ 191,469 |
| 15 | 62319 | 20.9 | 21693 | $ 216,934 |
| 16 | 64188 | 23.0 | 24579 | $ 245,786 |
| 17 | 66114 | 25.3 | 27848 | $ 278,476 |
| 18 | 68097 | 27.8 | 31551 | $ 315,513 |
| 19 | 70140 | 30.6 | 35748 | $ 357,476 |
| 20 | 72244 | 33.6 | 40502 | $ 405,020 |
| 21 | 74412 | 37.0 | 45889 | $ 458,888 |
| 22 | 76644 | 40.7 | 51992 | $ 519,920 |
| 23 | 78943 | 44.8 | 58907 | $ 589,070 |
| 24 | 81312 | 49.2 | 66742 | $ 667,416 |
| 25 | 83751 | 54.2 | 75618 | $ 756,182 |
| 26 | 86264 | 59.6 | 85675 | $ 856,755 |
| 27 | 88852 | 65.5 | 97070 | $ 970,703 |
| 28 | 91517 | 72.1 | 109981 | $ 1,099,806 |
| 29 | 94263 | 79.3 | 124608 | $ 1,246,081 |
| 30 | 97090 | 87.2 | 141181 | $ 1,411,809 |
| 31 | 100003 | 96.0 | 159958 | $ 1,599,580 |
| 32 | 103003 | 105.6 | 181232 | $ 1,812,324 |
| 33 | 106093 | 116.1 | 205336 | $ 2,053,363 |
| 34 | 109276 | 127.7 | 232646 | $ 2,326,460 |
| 35 | 112554 | 140.5 | 263588 | $ 2,635,880 |
| 36 | 115931 | 154.6 | 298645 | $ 2,986,452 |
| 37 | 119409 | 170.0 | 338365 | $ 3,383,650 |
| 38 | 122991 | 187.0 | 383368 | $ 3,833,675 |
| 39 | 126681 | 205.7 | 434355 | $ 4,343,554 |
| 40 | 130482 | 226.3 | 492125 | $ 4,921,247 |

***Note:***
Values shown are for illustrative purposes only.

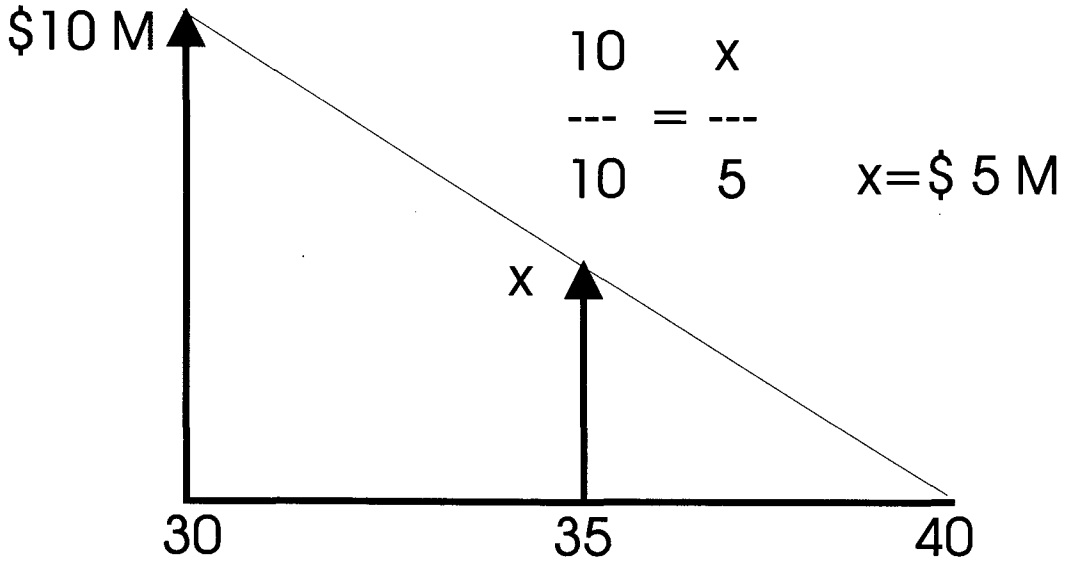
**Table 5.** Solution

| | Year | | | | | |
|---|---|---|---|---|---|---|
| **Alternative - A** | **0** | **20** | **30** | **35** | | |
| Agency Cost (Constant $) | 25.00 M | 10.00 M | 10.00 M | -5.00 M | | |
| Present Worth Factor | 1.000 | 0.4564 | 0.3083 | 0.2534 | | |
| Agency Cost (Present Worth) | 25.00 M | 4.564 M | 3.083 M | -1.267 M | | |
| Total NPV (Agency Cost) | 31.38 | | | | | |
| | | | | | | |
| User Cost (Constant $) | 7.333 M | 40.50 M | 141.2 M | | | |
| Present Worth Factor | 1.000 | 0.4564 | 0.3083 | | | |
| User Cost (Present Worth) | 7.333 M | 18.48 M | 43.53 M | | | |
| Total NPV (User Cost) | 69.34 M | | | | | |
| | | | | | | |
| Grand Total NPV (all costs) | 100.7 M | | | | | |

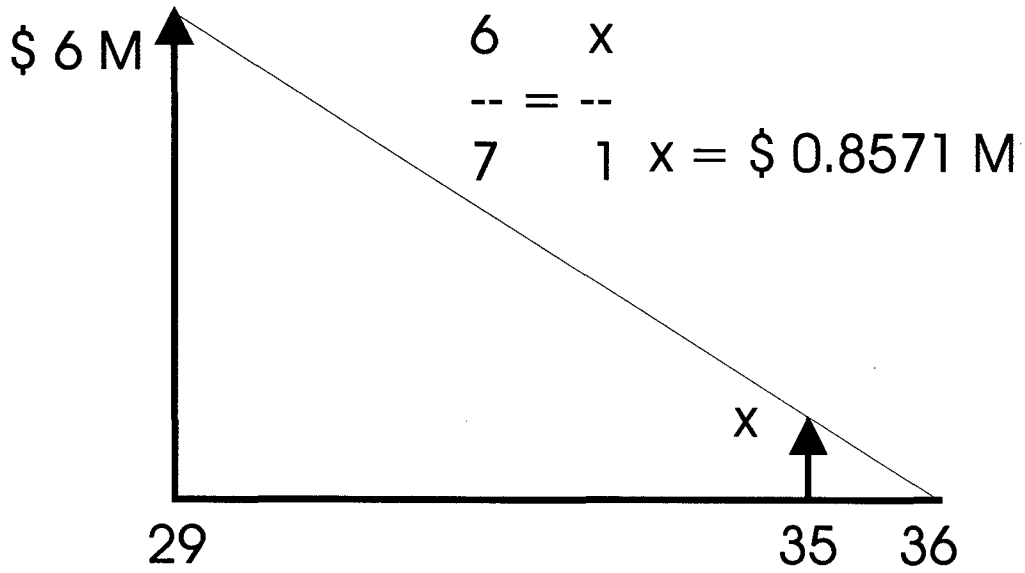
| | Year | | | | | |
|---|---|---|---|---|---|---|
| **Alternative - B** | **0** | **15** | **22** | **29** | **35** | |
| Agency Cost (Constant $) | 18.00 M | 6.000 M | 6.000 M | 6.000 M | -0.8571 M | |
| Present Worth Factor | 1.000 | 0.5553 | 0.4220 | 0.3207 | 0.2534 | |
| Agency Cost (Present Worth) | 18.00 M | 3.332 M | 2.532 M | 1.924 M | -0.2172 M | |
| Total NPV (Agency Cost) | 25.57 M | | | | | |
| | | | | | | |
| User Cost (Constant $) | 6.000 M | 15.18 M | 36.39 M | 87.22 M | | |
| Present Worth Factor | 1.000 | 0.5553 | 0.4220 | 0.3207 | | |
| User Cost (Present Worth) | 6.000 M | 8.429 M | 15.54 M | 27.97 M | | |
| Total NPV (User Cost) | 57.94 M | | | | | |
| | | | | | | |
| Grand Total NPV (all costs) | 83.51 M | | | | | |

# Selection of Construction Days.

| Alternative | Agency Cost | User Cost | Construction Days (Range) | Construction Days (Selection) |
|---|---|---|---|---|
| **Alt - A Initial** | 100,000 / day | **33,333 / day** | 200 to 220 | 220 |
| **Alt - A Rehab Year 20** | **200,000 / day** | 405,020 / day | 100 to 110 | 100 |
| **Alt - B Initial** | 200,000 / day | **33,333 / day** | 150 to 180 | 180 |
| **Alt - B Rehab Year 15** | **70,000 / day** | 216,934 / day | 70 to 100 | 70 |




$$\frac{10}{10} = \frac{x}{5} \qquad x = \$\ 5\ M$$




$$\frac{6}{7} = \frac{x}{1} \qquad x = \$\ 0.8571\ M$$