Speed Harmonization - Design Speed vs. Operating Speed

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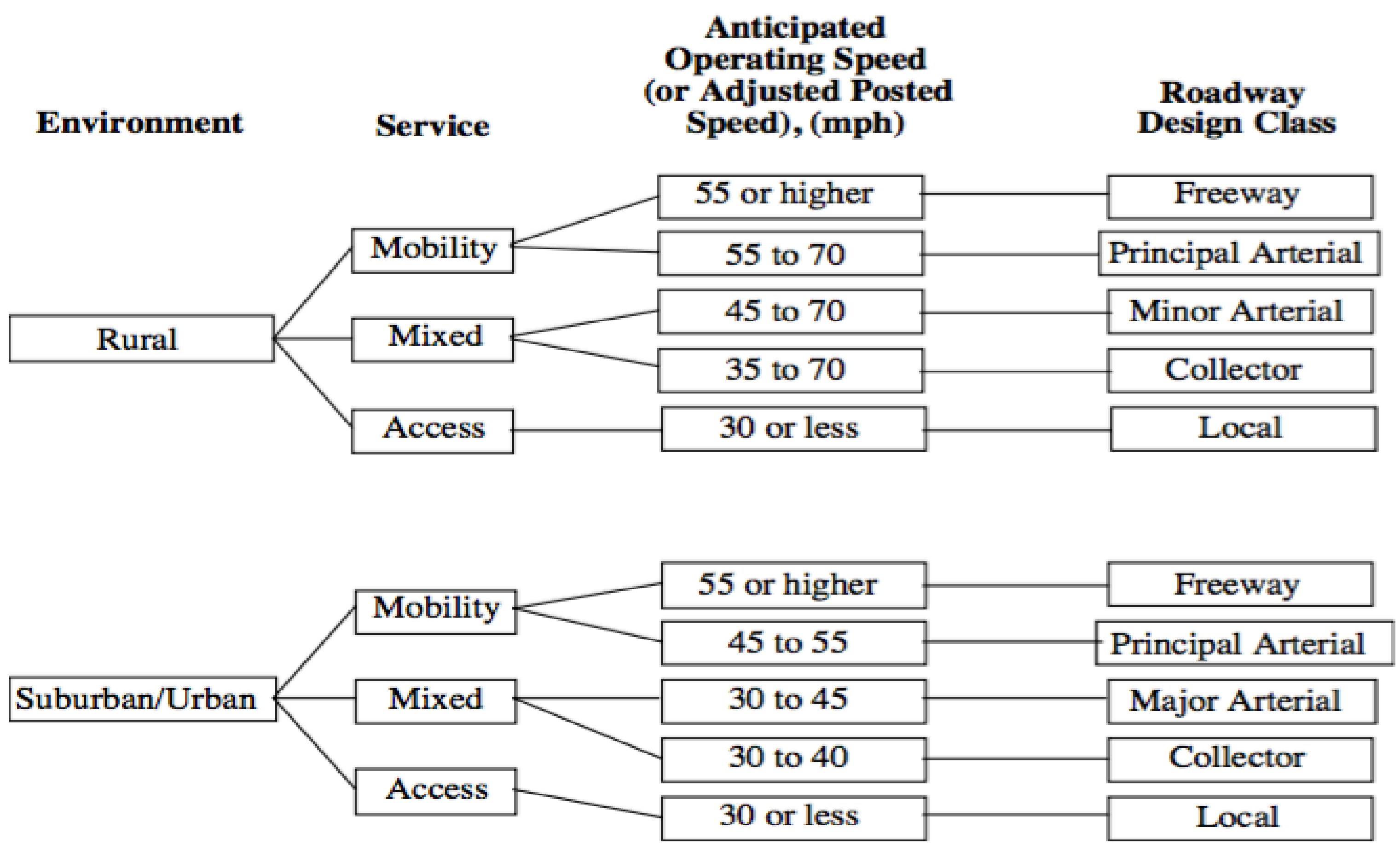
Introduction

- Good geometric design
  - appropriate mobility and land use access
  - high degree of safety
- Balance between mobility/accessibility and safety is often reflected by the “allowed” vehicle speed
- The design speed was used to determine the various geometric design features of a roadway.
  - critical for choosing super-elevation rates and radii of curves, sight distance, and the lengths of crest and sag vertical curves
  - Important for clean zone and guardrail design

Introduction

- Design speed often based on traffic volume and roadway functional classification
  - Potential discrepancy with the actual operating speed.
  - Anticipated operating speed – often used as design speed – may be lower than actual operating speed



Roadway design-class flow chart

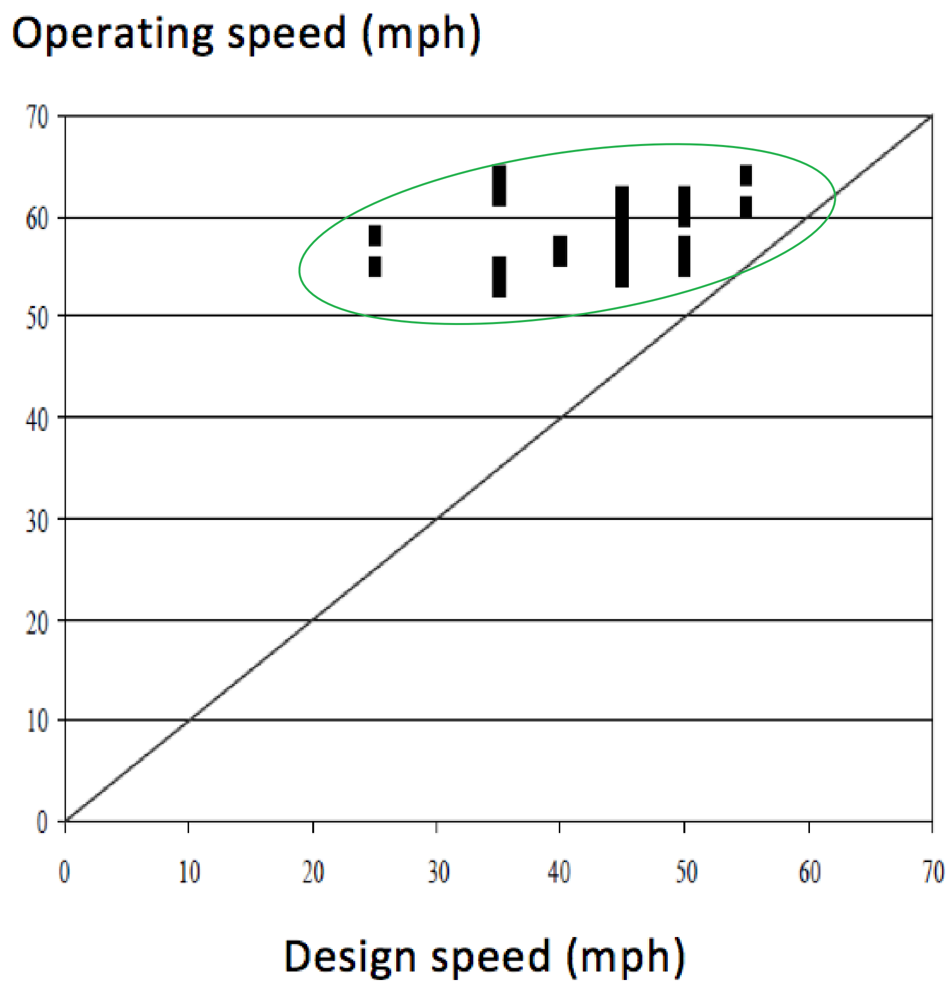
(Fitzpatrick et al. 2003)

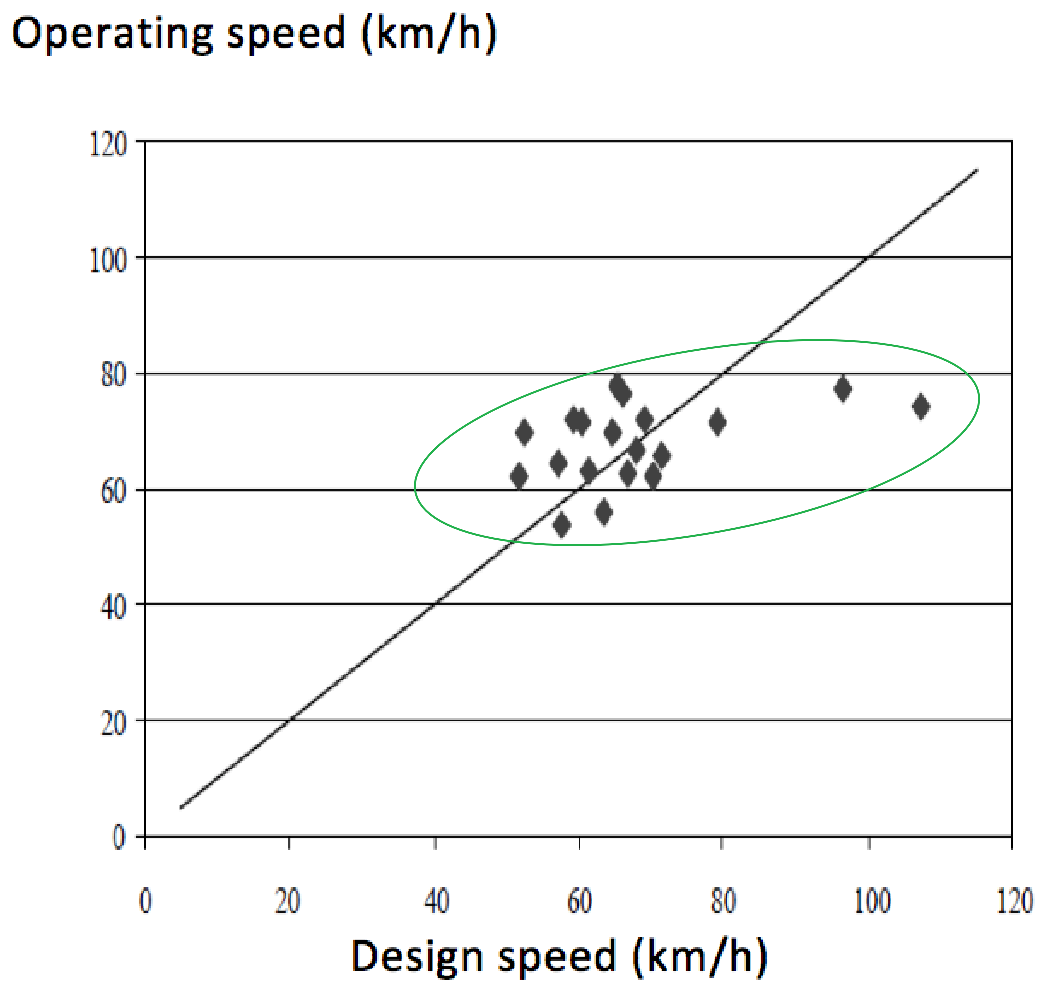
Introduction

- The operating speed of a road is the speed at which vehicles generally operate on that road -- "the speed at which drivers are observed operating their vehicles during free-flow conditions."
  - The 85th percentile of the observed speeds is the most frequently used measure of the operating speed.
- A survey conducted by Schroeder et al. (2013)
  - 9.8% of the interviewees drive often or at least sometimes 15 mph over speed limit on two-lane highways
  - 19.1% of the participants admitted to driving 15 mph higher than the posted speed limit on multi-lane highways.

Problem Statement

- Most ironically, the design speed often does not have a direct relationship with the operating speed (except for the extreme case of a very sharp roadway curve).





Design speed versus observed operating speed: (a) rural two-lane highway; (b) suburban arterial (Fitzpatrick et al. 2003).

Literature Review

- Empirical relationships among design speed, posted speed limit and operating speed.
- Factors used to select the design speed.
- Possible strategies to narrow the discrepancy between design speed and operating speed.
- Operating speed prediction models
- Characteristics that influence the roadway safety
- Design consistency evaluation criteria

IDOT Perspectives

- Interview with IDOT engineers

Date	Department	Representative	Title
24-Mar-16	Champaign County Highway Department	Mr. Jeff Blue	County Engineer
5-Apr-16	Sangamon County Highway Department	Mr. Brian Davis	Asst. County Engineer
		Mr. Brian Wright	Planning Engineer
7-Apr-16	Menard County Highway Department	Mr. Tom Casson	County Engineer

- Brief Summary of the Questions
  - Roadway Geometric Design

    e.g. front slope(Q2), guardrail(Q3), clear zone(Q7,Q8,Q9).
  - Design Speed, Operating Speed and Posted Speed Limit

    e.g. design speed and operating speed (Q14, Q16, Q18, Q19), posted speed limit(Q12, Q15).
  - Safety and Improvements

    e.g. safety level (Q22), improvements (Q21, Q23).

Summary of Interviews

- Selected Questions and Answers
  - Existence of Disparities between Design Speed and Operating Speed

19. On two lane rural highway alignments, is there empirical evidence of disparities between design speeds and operating speeds?

<u>Champaign County Highway Department Response</u>:

Yes, the operating speed may be 5- 10 mph greater.

<u>Sangamon County Highway Department Response</u>:

Based on our experience, the answer should be yes.

<u>Menard County Highway Department Response</u>:

Yes, the operating speed is larger than design speed and the statutory speed limits.

Summary of Interviews

- Selected Questions and Answers
  - Design Speed on Low Volume Roads

14. What is your Agency's policy regarding the use of the design speed for the design of low volume roads when you know the operating speeds are much higher?

<u>Champaign County Highway Department Response</u>:

1. Operating speed is not included in design.
2. Balance between safety and the cost.

<u>Sangamon County Highway Department Response</u>:

1. Design on speeds that are close to the posted speed limits.
2. Post a lower speed limit.

<u>Menard County Highway Department Response</u>:

1. Cost is a very important factor.
2. The ADT is very low, which is safer for drivers.

Summary of Interviews

- Selected Questions and Answers
  - The Selection of Design Speed

18. What method is used by your Agency to determine the design speed? Does it give even a minor consideration to the operating speed?

Champaign County Highway Department Response:

The functional classification in Bureau of Local Roads and Streets Manual(BLRS) should be used.

Sangamon County Highway Department Response:

The Bureau of Local Roads and Streets Manual (BLRS) is used. It doesn't consider operating speed.

Menard County Highway Department Response:

The Bureau of Local Roads and Streets Manual(BLRS) is used.

Summary of Interviews

- Selected Questions and Answers
  - Is Clear Zone Sufficient?

8. What is your opinion regarding the clear zone requirements for culverts on a low volume, high operating speed roadway? Do you think a 6 or 7-foot clear zone policy is sufficient for these types of roadways?

<u>Champaign County Highway Department Response</u>:

For new projects: may not be sufficient.

For maintenance projects: too costly to widen the clear zone.

<u>Sangamon County Highway Department Response</u>:

Follow the Bureau of Local Roads and Streets Manual (BLRS) rules.

<u>Menard County Highway Department Response</u>:

May not be sufficient, but we are unable to extend it without enough right of way.

Summary of Interviews

- Selected Questions and Answers
  - Safety and Improvements

23. What would you recommend to improve the safety level?

<u>Champaign County Highway Department Response</u>:

1. Removing fixed objects to reduce fatalities.
2. Proper signage.
3. Proper maintenance.

<u>Sangamon County Highway Department Response</u>:

1. Speed enforcement.
2. Zero tolerance of alcohol.

<u>Menard County Highway Department Response</u>:

Adding the advisory speed on curves and adding chevrons.

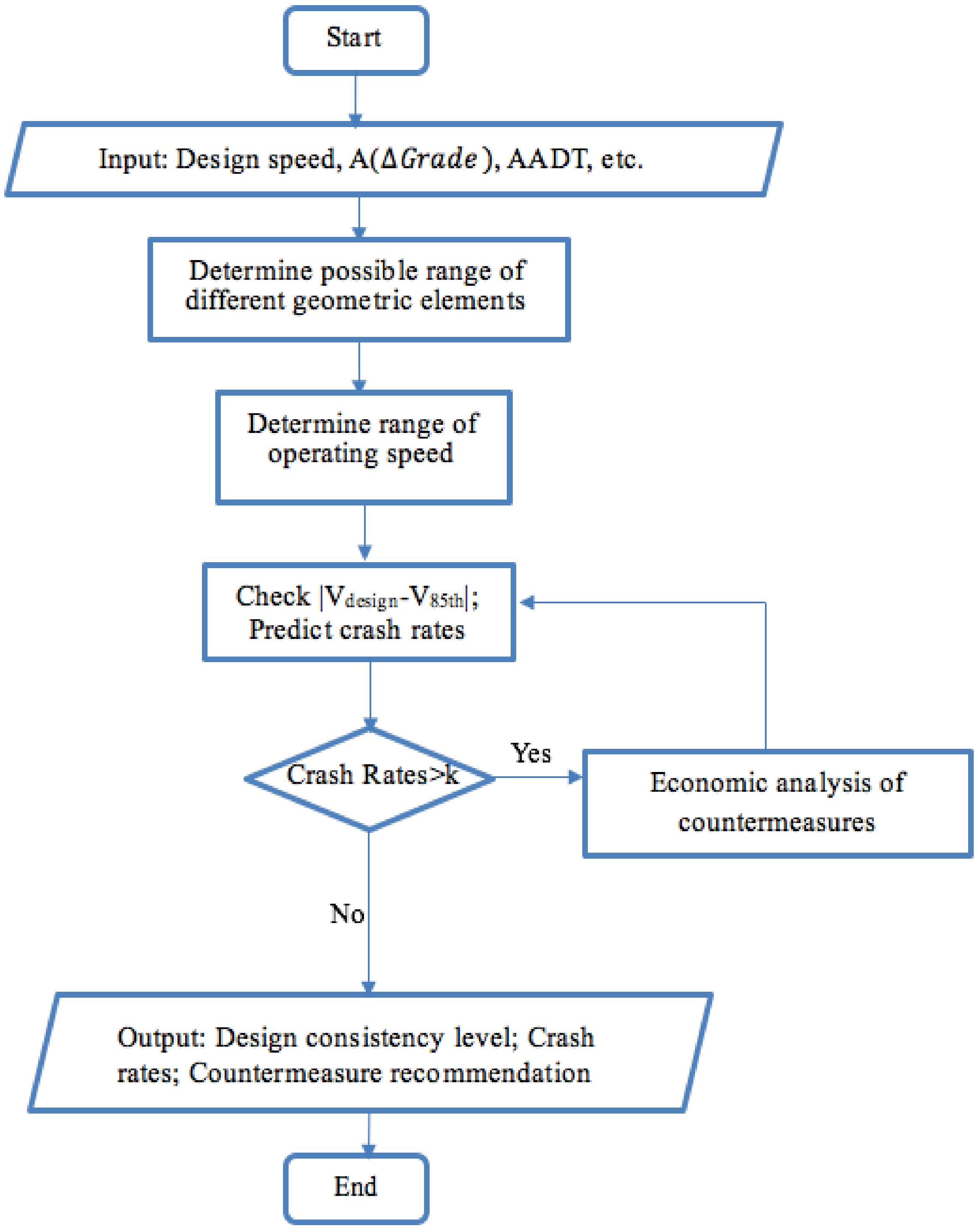
Challenges

- Discrepancy between design speed and operating speed is potentially problematic from a safety point of view.
  → Check consistency level between design speed and operating speed. Reduce crash rates using countermeasures
- Safety features of geometric design (such as clear zone and guardrail length of need) are determined based on the lower design speed rather than the actual operating speed.
  → Determine whether higher design speed is appropriate through interview and simulation.
- No existing framework could evaluate both the safety and benefit/cost for different countermeasures
  → Incorporate economic analysis into the framework

Methodology

For existing/new site of interest

- Step 1: Simulate acceptable geometric design
- Step 2: Predict distribution of operating speed
- Step 3: Predict crash rate
- Step 4: If crash rate is large, identify and assess safety improving countermeasures based on economic analysis
- Output: Design consistency level, crash rates, countermeasure recommendation



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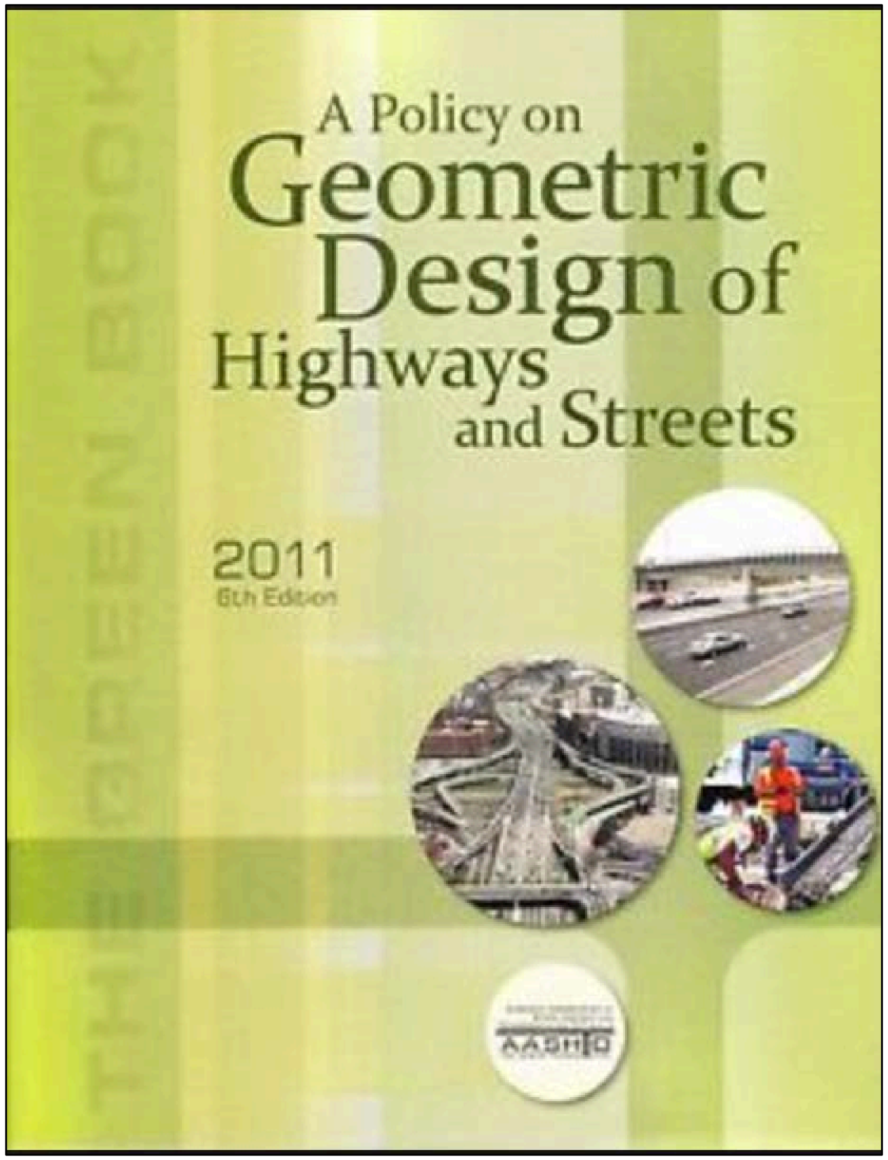
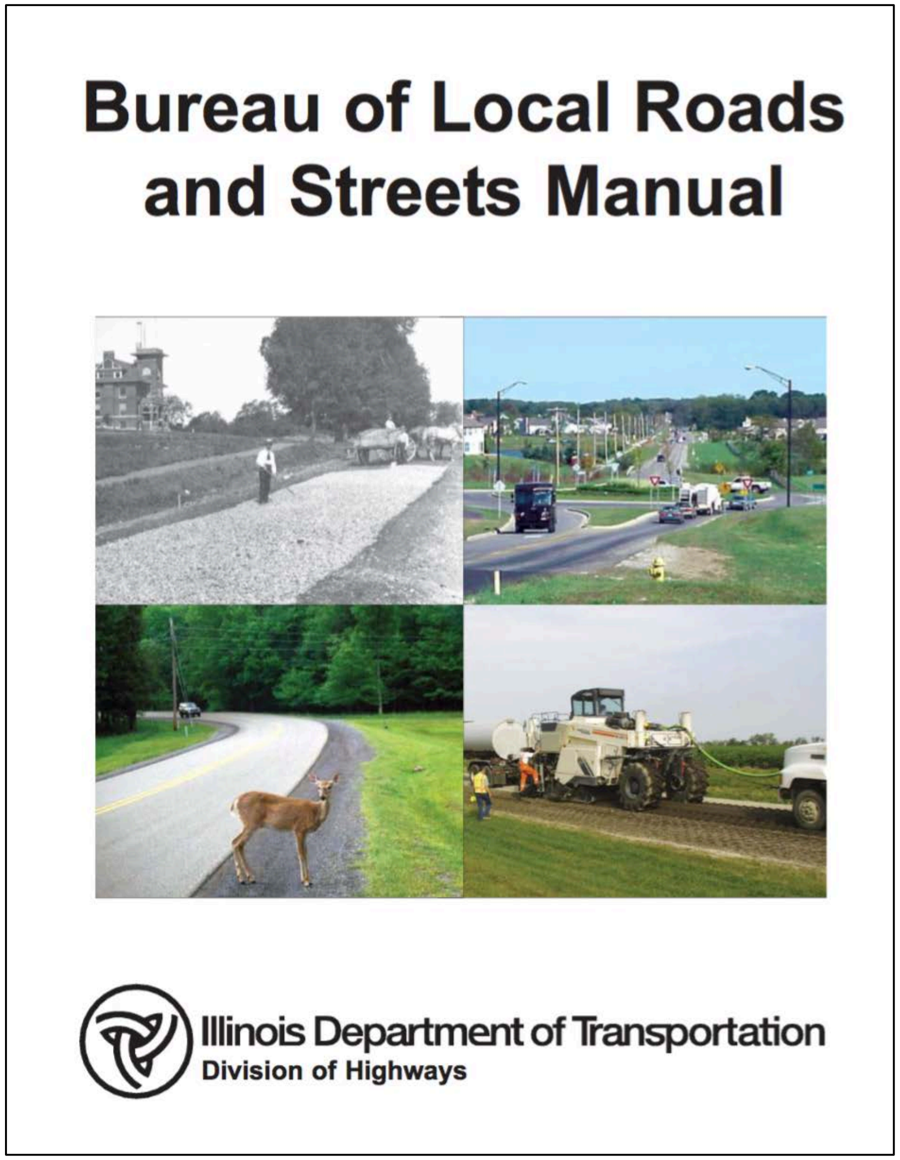
Step 1: Simulate Acceptable Geometric Design

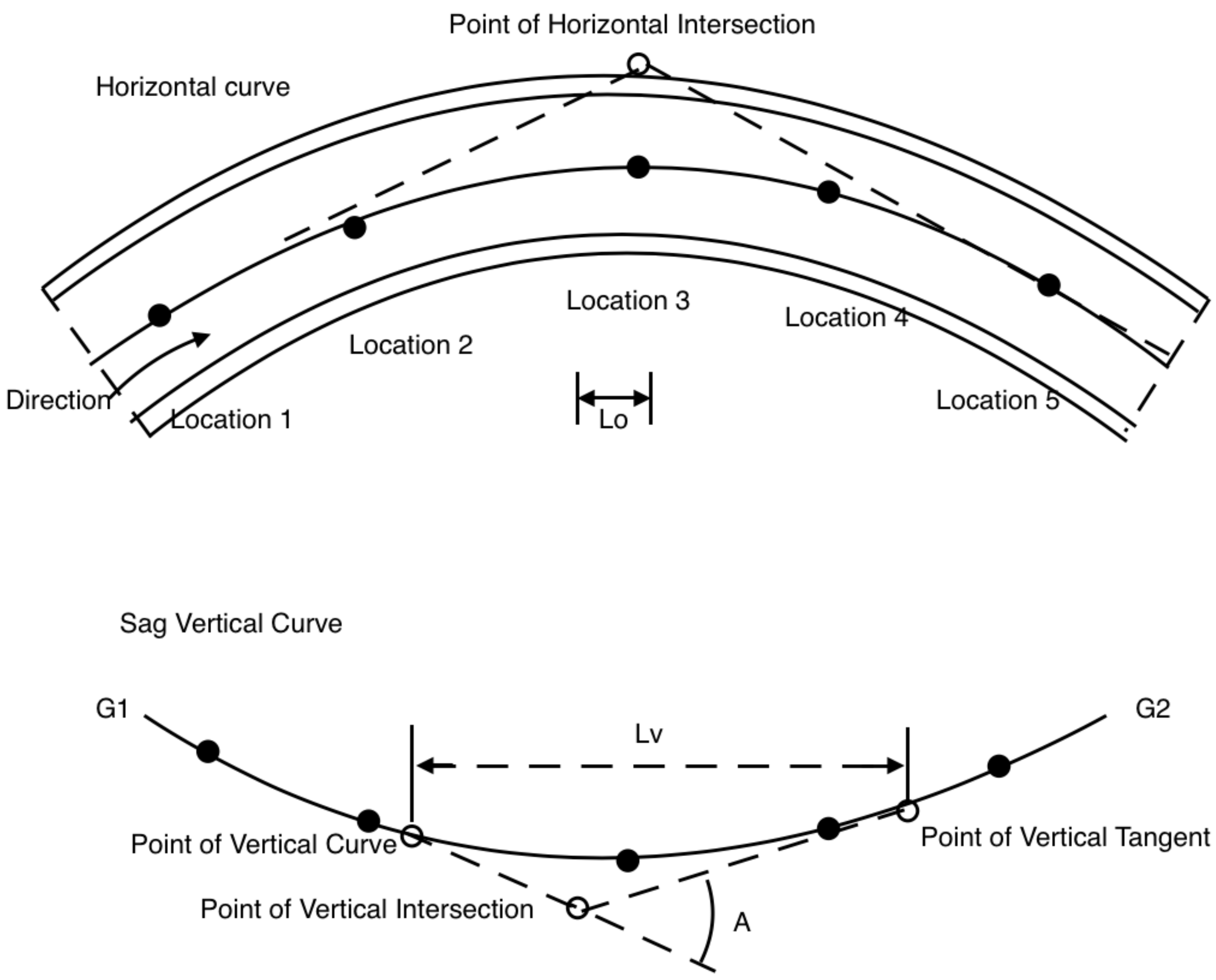
- Design Guides





Example

- An Illustrative Example



Summary of Inputs

Input	Value	Description
A	2	Absolute value of the difference in grades $\|G_1 - G_2\|$
V	50mph	Design speed
G1	-1	First grade in the direction of travel
G2	1	Second grade in the direction of travel
L_0	262ft	Horizontal distance between the point of vertical intersection and the point of horizontal intersection
AADT	1000vpd	Annual average daily traffic
LW	11ft	Lane Width
SW	5ft	Shoulder Width
Sag/Crest	Sag	Sag Vertical Curve

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Example

- Simulate Acceptable Designs

  Given the absolute value of algebraic difference, design speed, AADT and other inputs, the following will be conducted:

  - Step 1. Calculate stopping sight distance.
  - Step 2. Check acceptable ra
  - Step 3. Check acceptable ra

$$d = 1.47Vt + \frac{V^2}{30((\frac{a}{32.2}) \pm G)}$$

t = brake reaction time 2.5 s

V = design spee

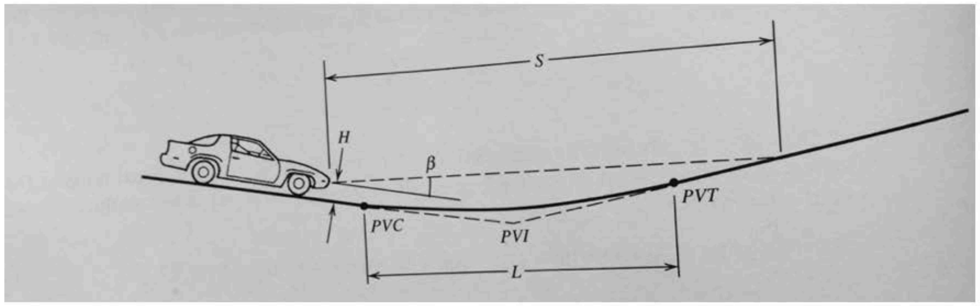
a = deceleration

G = percent of g

$$SSD = \frac{\pi R_V}{90}$$

M_s: middle o

R_v: radius t the road)



Appl acce

$$R_v = \frac{V^2}{g(f_s + \frac{e}{100})}$$

e = rate of roadway superelevation, perc

g = graviational constant, 32.2ft/s^2

f_s = coefficient of side friction(unitless)

V = design speed(ft/s)

R_V = radius defined to the vehicle's trave

For $SSD < L,\ L_m = \frac{A * SSD^2}{200(H + S\ tan\beta)^2}$

$SSD > L,\ L_m = 2S - \frac{200(H + SSD * tan\beta)}{A}$

H = height of headlight in ft(m)

β = inclined angle of headlight beam in degree

L_m = minmum length of vertical curve in ft

A = absolute value of the difference in grades $|G_1 - G_2|$

Step 2: Predict Distribution of Operating Speed

- General roadway profile may include curves and tangent segments
- Speed varies on tangents and horizontal curves (Ottesen et al., 2000; Lamm et al., 1992; de Oña et al, 2013; Camacho-Torregrosa et al., 2013)

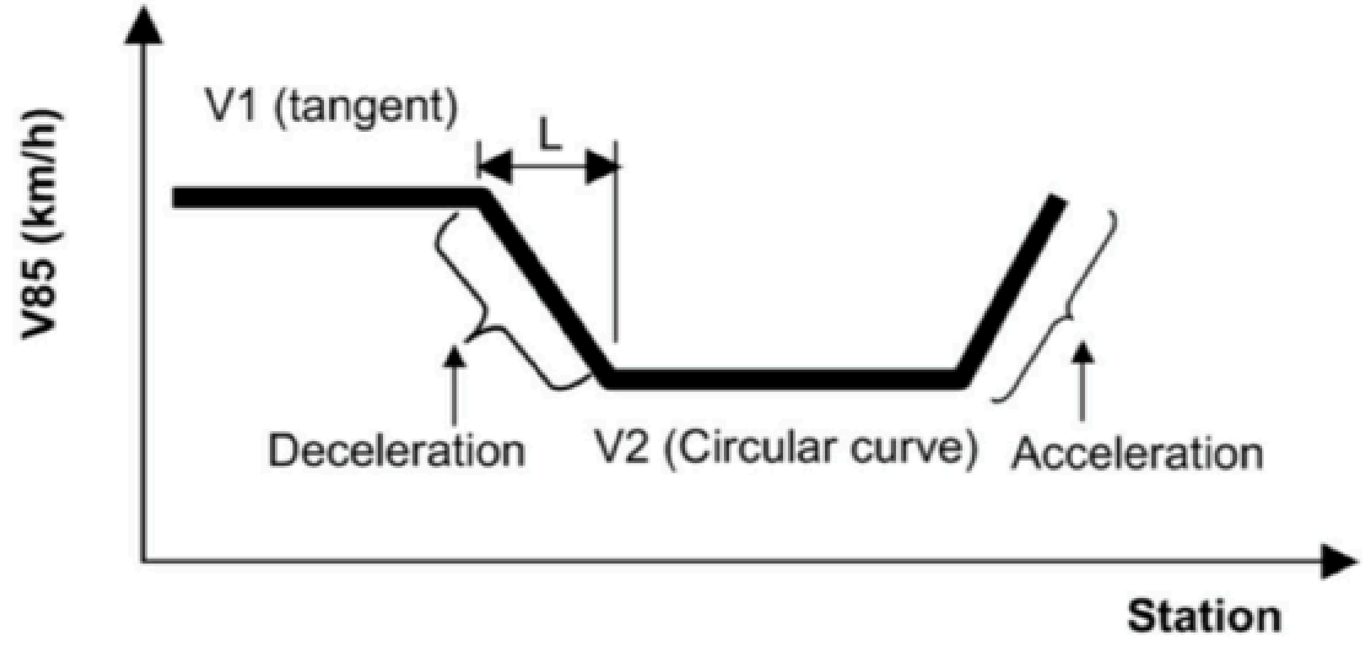
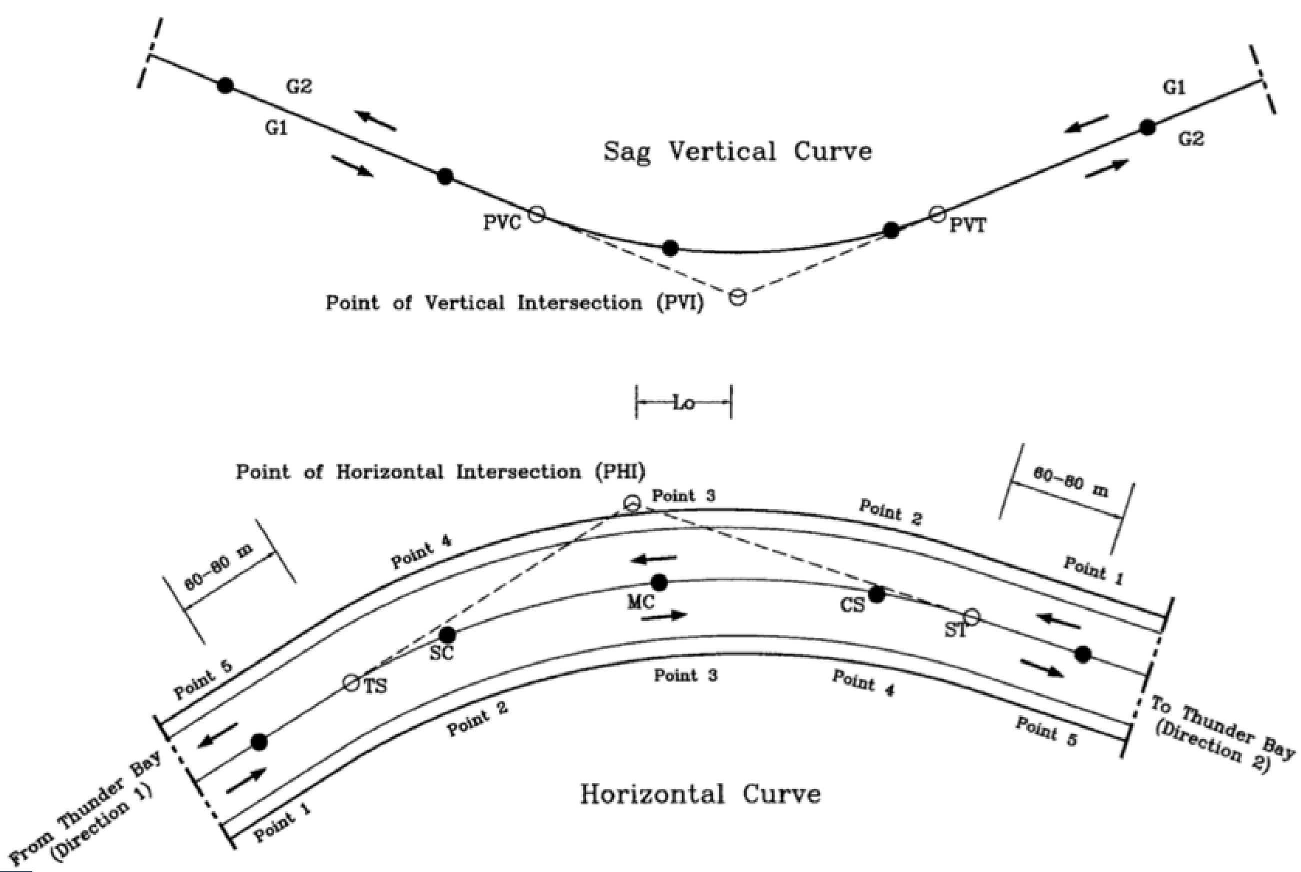


Figure: Speed profile (Source: Castro et al.,2008)

Step 2: Predict Distribution of Operating Speed

- 3D horizontal and vertical curves (Gibreel et al., 2001)

$$V_S1 = 91.81 + 0.010r + 0.468\sqrt{L_V} - 0.006G_1^3 - 0.878\ln(A) - 0.826\ln(L_0)$$
$$V_S2 = 47.96 + 7.217\ln(r) + 1.534\ln(L_V) - 0.258G_1 - 0.653\text{A} - 0.008L_0 + 0.020\text{exp}\,(e)$$
$$V_S3 = 76.42 + 0.023\text{r} + 2.300\times10^{-4}K^2 - 0.008\exp(A) - 1.230\times10^{-4}{L_0}^2 + 0.062\text{exp}\,(e)$$
$$V_S4 = 82.78 + 0.011\text{r} + 2.067\ln(K) - 0.361G_2 + 0.036\text{exp}\,(e) - 1.091\times10^{-4}{L_0}^2$$
$$V_S5 = 109.45 - 1.257G_2 - 1.586\ln(L_0)$$



V_S1 *to* V_S5 = predicted 85th percentile operating speed at point 1 to point 5(km/h).
r = radius of horizontal curve(m),
L_V = length of vertical curve(m)
e = superelevation rate(percent),
A = algebraic difference in grades(percent)
K = rate of vertical curvature(m),
G_1 and G_2 = first and second grades in the direction of travel in percent
L_0 = horizontal distance between point of vertical intersection and point of horizontal intersection(m)

Step 2: Predict Distribution of Operating Speed

- Tangent Segments

$$V_{85T} = V_{85C} + (1 - e^{-\lambda L}) \cdot (V_{des} - V_{85C})$$

$V_{des} =$ desired speed(km/h), assumed 110km/h from the literature;

$V_{85C} =$ 85th percentile speed on previous curves obtained from the proposed model;

$L =$ tangent length(m).

$R =$ curve radius(m).

$$\lambda = 0.00135 + (R - 100) \cdot 7.00625 \cdot 10^{-6}$$

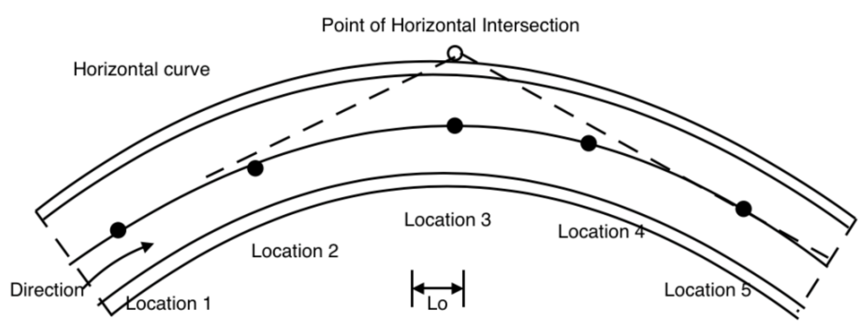
Example

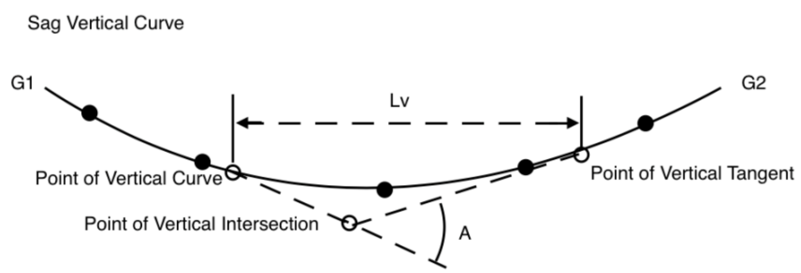
- Simulate and normalize the probability distribution of speed at each location
- Compute the mean and standard deviation

$$v_j = \int_{-\infty}^{+\infty} v f_j(v) dv$$

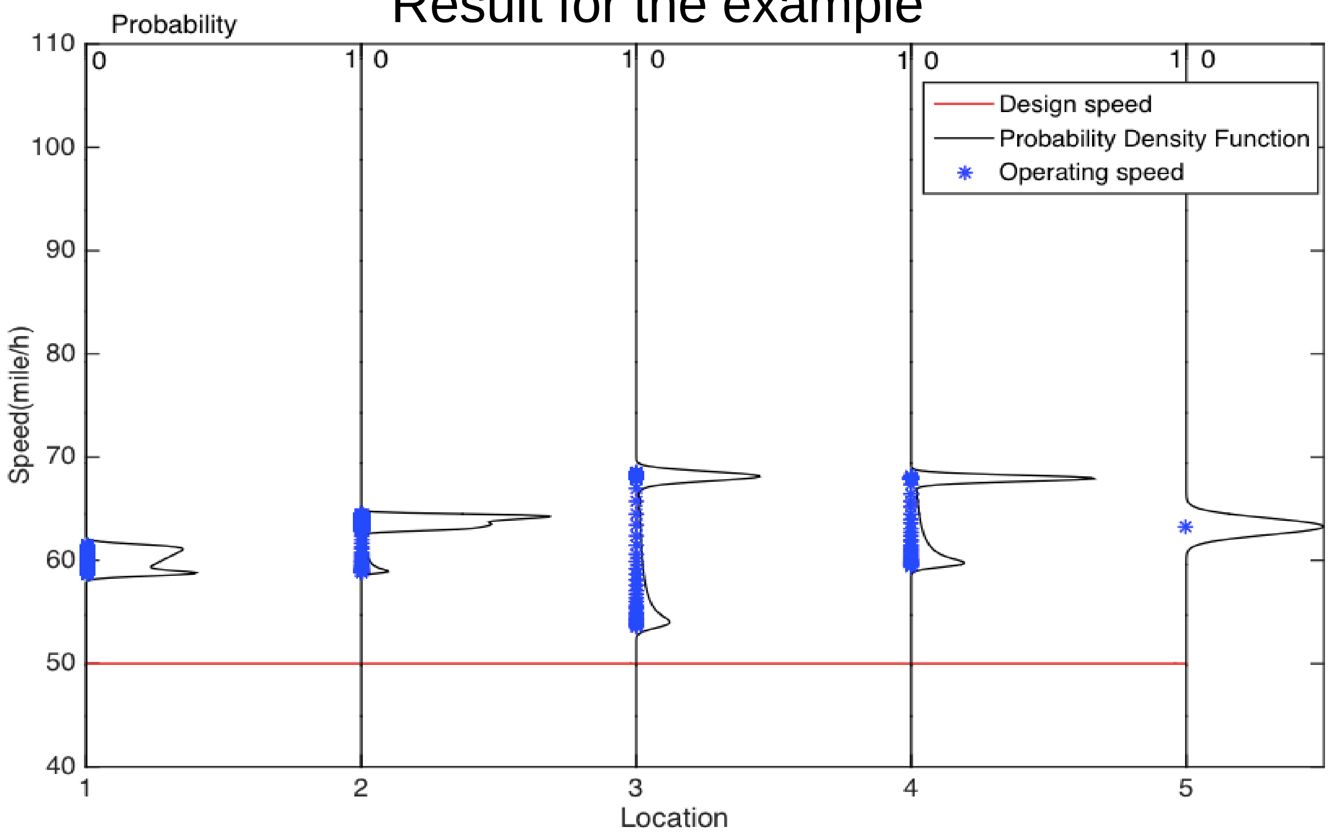
$$SD_j = \sqrt{\int_{-\infty}^{+\infty} (v - v_j)^2 f_j(v) dv}$$

$j =$ index of location. (1 to 5)
$f_j(v) =$ normalized probability of density function at location j
$v_j =$ mean of predicted operating speed at location j
$SD_j =$ standard deviation of predicted operating speed at location j





Result for the example



Evaluate Design Consistency

- Criterion 1: Difference between design speed and operating speed
- Criterion 2: Difference in operating speed on successive elements of the road
- Criterion 3: Driving dynamics (sufficient side friction)

TABLE: Design consistency evaluation criteria (Hassan, 2004)

Consistency Level	Criterion 1(km/h)	Criterion 2(km/h)	Criterion 3
Good	$\lvert V_{85} - V_d \rvert \leq 10$	$\lvert V_{85k} - V_{85\,k+1} \rvert \leq 10$	$f_R - f_{RD} \geq +0.01$
Fair	$10 < \lvert V_{85} - V_d \rvert \leq 20$	$10 < \lvert V_{85k} - V_{85\,k+1} \rvert \leq 20$	$+0.01 > f_R - f_{RD} \geq -0.04$
Poor	$\lvert V_{85} - V_d \rvert > 20$	$\lvert V_{85k} - V_{85\,k+1} \rvert > 20$	$-0.04 > f_R - f_{RD}$

In the table, V_{85} is the operating speed, V_d is the design speed, V_{85k} and V_{85k+1} are the operating speeds on consecutive road sections k and k+1. Parameters f_R and f_{RD} are respectively the assumed and demanded side frictions on a section.

Step 3: Predict Crash Rate

- Crash rate on curves (Garber and Ehrhart, 2000)

Model 1: ln (crash rate) = 44.323 - 25755.82/SD^{2} +93793.11/SD^{4}-8.686*10^{-3} *FPL^{2}+0.106/SD^{2} *FPL^{2}- 1.68710^{-8}*FPL^{4} +469.071/LW$^{0.5}$+44529.25 /SD^{2}/LW$^{0.5}$ + (1.445*10^{-2} *FPL^{2} /LW$^{0.5}$-956.114/LW$^{0.5}$)^{2}-93.415*SW-660.808/SD^{2} *SW+5.626*10^{-5} *FPL^{2}*SW +152.084/LW$^{0.5}$*SW+3.475*SW^{2}, R^2=0.9864, AIC=-48.715

Model 2: 1/ crash rate$^{0.5}$ = 1132.667 -3035.839/SD-13380.54/SD^{2}-1.436*10^{-3} *FPL^{2} - 4.313* 10^{-2}/SD *FPL^{2} +1.752*10^{-7}*FPL^{4} -9519309/MEAN^{2} –6956803/SD/MEAN^{2}- 71.254*FPL^{2}/MEAN^{2}-1.060174*10^{9}/MEAN^{4}-210.998*LW +1963.584/SD*LW+3.751*10^{-3}*FPL^{2}*LW+ 3334646/MEAN^{2}*LW-65.918*LW^{2}, R^2=0.9817, AIC=18.247

Model 3: 1/ crash rate$^{0.5}$ =23635.61-17107.41/SD-12605.73/SD^{2}-1.184*FPL- 10.318/SD*FPL+2.621*10^{-3}*FPL^{2}-25345.75*LW$^{0.5}$ + 10829.1/SD*LW$^{0.5}$ +1.051*FPL *LW$^{0.5}$ +6744.683*LW-156.286*SW^{2} +199.0262/SD*SW^{2}-8.073*10^{-2}*FPL*SW^{2}+ 89.694*LW$^{0.5}$ *SW^{2}-2.945*SW^{4}, R^2=0.9697, AIC=28.845

Model 4: 1/ crash rate =1331486-1365.183*SD-5.771*SD^{2}-0.541*FPL^{2}+ 6.709*10^{-3} *SD*FPL^{2}+3.204*10^{-6}*FPL^{4}-4744279/LW$^{0.5}$ + 2739.721*SD/LW$^{0.5}$ +0.873*FPL^{2} /LW$^{0.5}$ +4219166/LW+1871.932 *SW^{2} -23.51972*SD*SW^{2}-0.031*FPL^{2}*SW^{2}- 2230.496/LW$^{0.5}$ *SW^{2}-47.560*SW^{4}, R^2=0.9312, AIC=171.06

Notation

AIC= Akaike's information criterion

FPL = flow per lane (vph)

LW = lane width (m)

MEAN = the mean speed (km/h)

R^2 = coefficient of determination

SD = standard deviation of speed (km/h)

SW = shoulder width (m)

Step 3: Predict Crash Rate

- Crash Rates on Tangent (Camacho-Torregrosa et al., 2013)

$$ECR = \frac{1}{2.40939 + 0.00403287 * (\bar{v}_{85}^2 / \Delta\bar{v}_{85})}$$

Where

ECR = estimated crash rates (crashes/10^6 vehicles -km/10 years)

$\bar{v}_{85}$ = Average operating speed

$\overline{\Delta v_{85}}$ = Average speed reduction, the average value of all speed reduction processes at each road segment.

Result for the example

$\bar{v}_{85}$ (mile/h)	62.6
$\overline{\Delta v_{85}}$ (mile/h)	2.031
ECR * (crash/10^6 veh-mile)	0.1078

*Will be adjusted by shoulder width and lane width

Step 4: Identify and Assess Countermeasures

- Possible strategies to reduce the discrepancy between design speed and operating speed
  - Change design speed (European countries and Australia)
    - (1) Design a preliminary alignment based on a given design speed
    - (2) Estimate the operating speeds (85th percentile speeds)
    - (3) Check the difference on successive curves.
    - (4) Revise the geometric alignment to narrow the gap to acceptable levels.
  - Improve roadway design (recommended)
    - Identify relevant design features
    - Use Crash Modification Factors adjust the base predictions according to the changed roadway features

Step 4: Identify and Assess Countermeasures

- Geometric Characteristics that Influence Safety

Lane Width.

Garber et al. (1993) showed that larger lane width could improve safety. However, several researchers did not observe such a relationship (Dart and Mann, 1970). Noland et al.(2004) found that lane widths appears to be associated with increased fatalities.

Shoulder Width.

Raff (1953) ,Perkins (1956) and Noland et al. (2004) claimed that larger shoulder width could reduce the crash rates; Cirillo et al. (1969) did not observe such a relationship.

Degree of curvature.

Fink et al. (1995) showed that crash rate increases almost linearly with degree of curvature.

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Step 4: Identify and Assess Countermeasures

- Crash Modification Factors for Shoulder Width

$$CMF_{2r} = (CMF_{wra} \times CMF_{tra} - 1.0) \times p_{ra} + 1.0$$

CMF_{2r} = crash modification factor for the effect of shoulder width and type on total crashes;

CMF_{wra} = crash modification factor for related crashes (i.e., single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes), based on shoulder width;

CMF_{tra} = crash modification factor for related crashes based on shoulder type;

p_{ra} = proportion of total crashes constituted by related crashes. (Illinois default value=0.372)

Step 4: Identify and Assess Countermeasures

- Crash Modification Factors for Lane Width

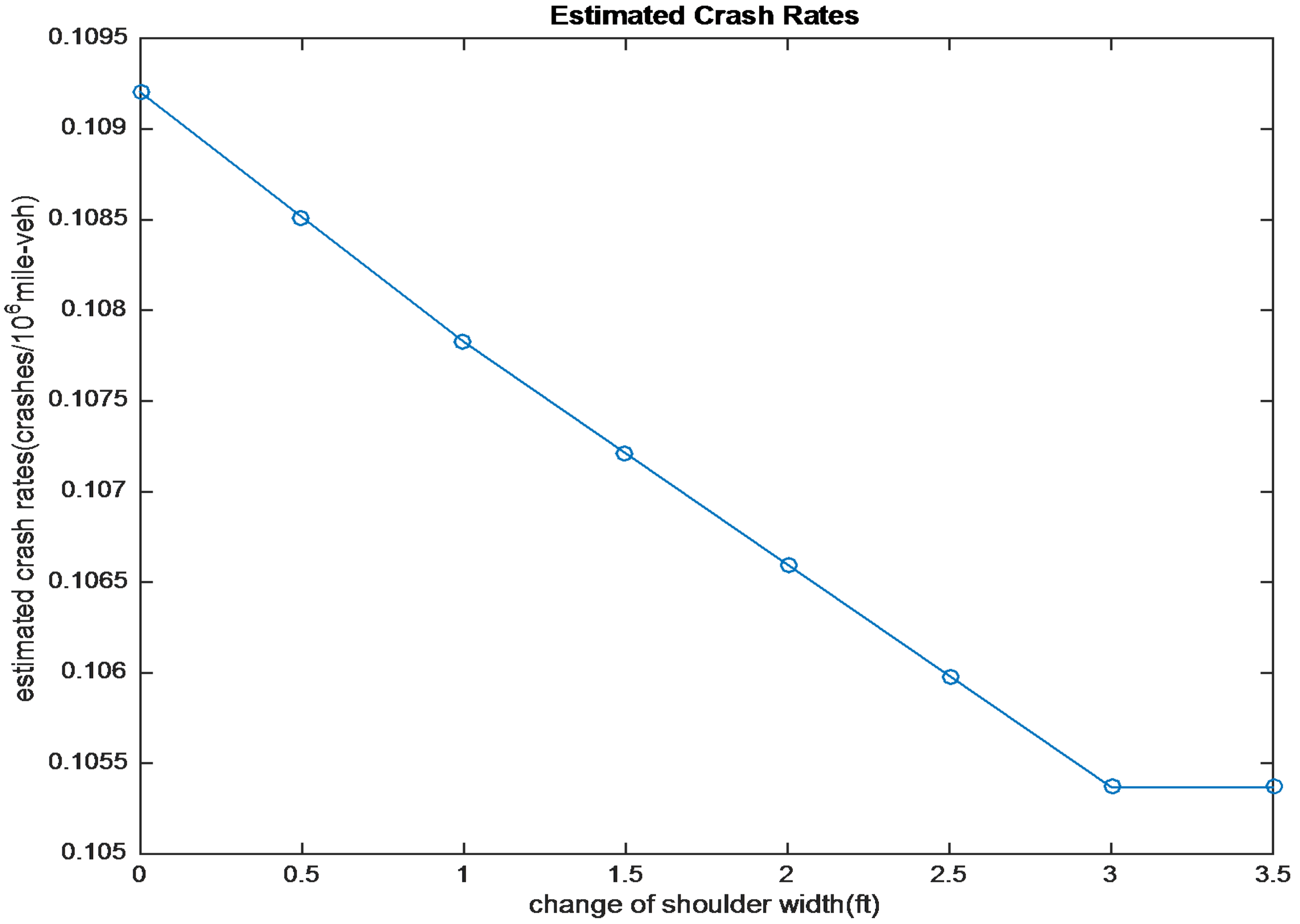
	AADT (vehicles per day)		
Lane Width	**< 400**	**400 to 2000**	**> 2000**
9 ft or less	1.05	$1.05 + 2.81 \times 10^{-4}(\text{AADT} - 400)$	1.50
10 ft	1.02	$1.02 + 1.75 \times 10^{-4}(\text{AADT} - 400)$	1.30
11 ft	1.01	$1.01 + 2.5 \times 10^{-5}(\text{AADT} - 400)$	1.05
12 ft or more	1.00	1.00	1.00

Note: The collision types related to lane width to which this CMF applies include single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.

Example

- Safety Impacts of Widening Shoulder

Estimated Crash Rates
vs.
Shoulder Width



Step 4: Identify and Assess Countermeasures

- Benefit & Cost Analysis
  - Safety Benefit

$$b_i = C_a \cdot R_i \cdot AADT \cdot L \cdot ECR \cdot 365 \cdot \frac{(1+s)^{n_i}-1}{s(1+s)^{n_i}},$$

where

b_i = present value of safety benefits of countermeasure i ($)

C_a = average cost of each accident ($)

R_i = CRF (crash reduction factor) value for countermeasure i, which is the expected percent decrease in crash rates due to countermeasure implementation. Calculated as $(1 - CMF)$,

$AADT$ = average annual daily traffic (vehicles/day)

ECR = estimated crash rates (crashes/10^6 vehicles -mile)

L = roadway segment length (mile)

s = minimum attractive rate of return expressed as a decimal fraction

n_i = service life of countermeasure i

Example

- Benefit & Cost Analysis
  - Cost

$$c_i = C_i \cdot \Delta x_i,$$

where c_i = cost of countermeasure i (dollars),
C_i = unit cost of countermeasure i (dollars/unit),
Δx_i = units of improvement of countermeasure i.

  - Countermeasure Selection

$$\text{maximize} \sum_{i \in I} b_i \cdot x_i,$$
$$s.t. \sum_{i \in I} c_i x_i \le D,$$
$$x_i \in \{0, 1\}, \forall i \in I.$$

0-1 Knapsack Problem: Can be solved using dynamic programming methods.

where x_i= decision variable for countermeasure i,
b_i = present value of safety benefits of countermeasure i,
c_i = cost of countermeasure i,
D = agency's budget,
I = set of countermeasure candidates.

Example

Countermeasure Evaluation

Consider a 5-mile roadway section, and three countermeasure candidates including:
(1) widening shoulder width from 5ft to 6ft,
(2) widening lane width from 11ft to 12ft, and
(3) installing advisory speed sign (assuming there is no speed sign installed initially).

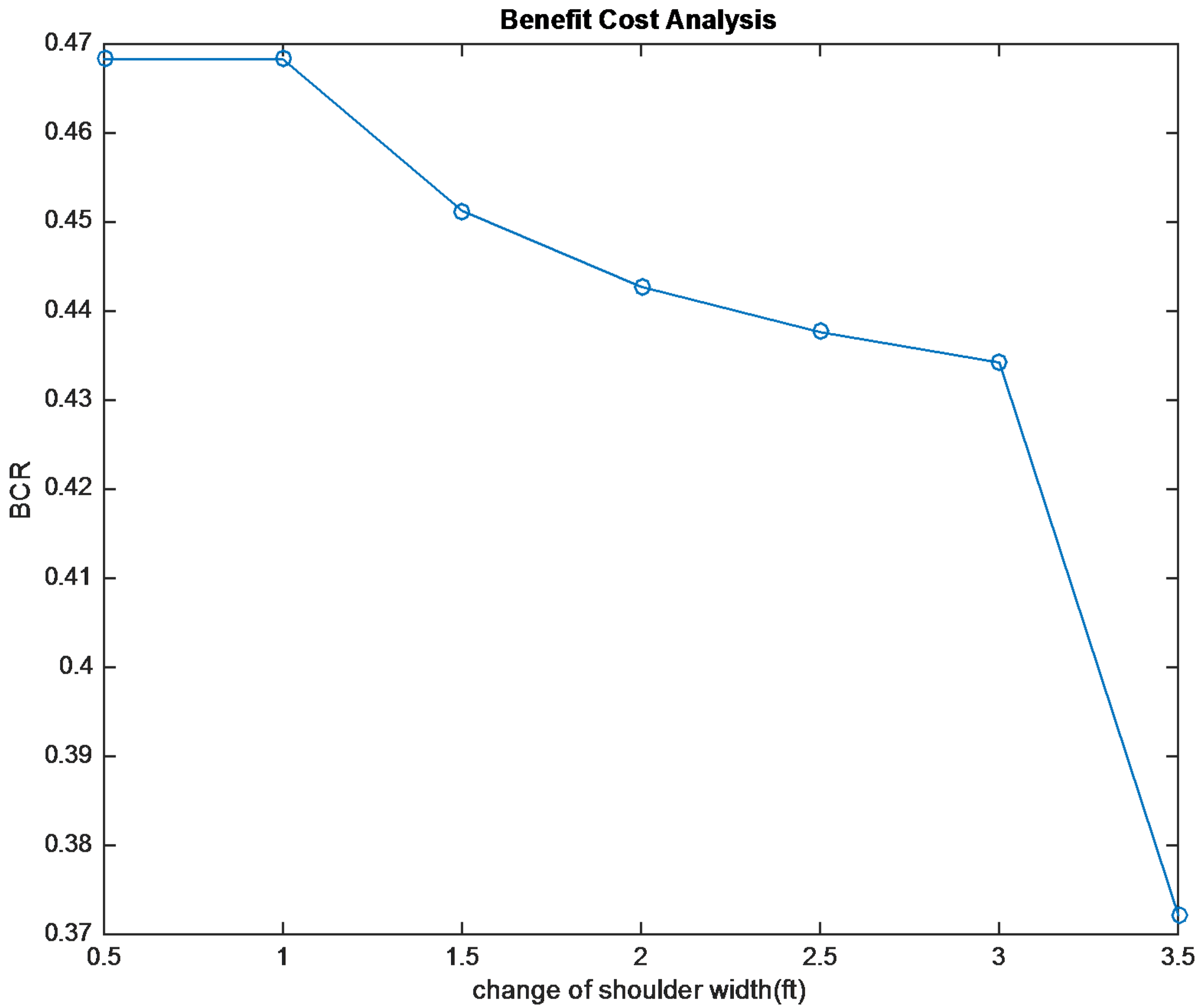
Table: Cost information

Item	Value	Source
Crash	1,565,439 $/crash	IDOT
Shoulder Widening	4.33$/ft^2	Illinois Data
Lane Widening	4.44$/ft^2	Ohio Data
Advisory Speed Sign	2000$	Internet
Budget	150,000$	

Example

- Benefit & Cost Analysis (shoulder width)

Benefit Cost Ratio
vs.
Shoulder Width



Example

Countermeasure Evaluation

Countermeasure	Benefit b_i/\$	Cost c_i/\$	Life cycle/y	BCR_i	Recommendation
Widening shoulder width from 5ft to 6ft	53224	113653	20	0.47	Not to select
Widening lane width from 11ft to 12ft	83244	116541	20	0.75	Select
Installing advisory speed sign	177245	2000	5	88.6	Select

Countermeasure	Benefit b_i/\$	Cost c_i/\$	Life cycle/y	BCR_i	Recommendation
Widening shoulder width from 5ft to 6ft	53224	113653	20	0.47	
Widening lane width from 11ft to 12ft	83244	116541	20	0.75	
Installing advisory speed sign	177245	2000	5	88.6	

Using Countermeasure 2 & 3

0.1092 crashes/10^6veh-mile

→ 0.0938 crashes/10^6veh-mile

Crash Rates Reduced

Case Study: Clear Zone and Guardrail

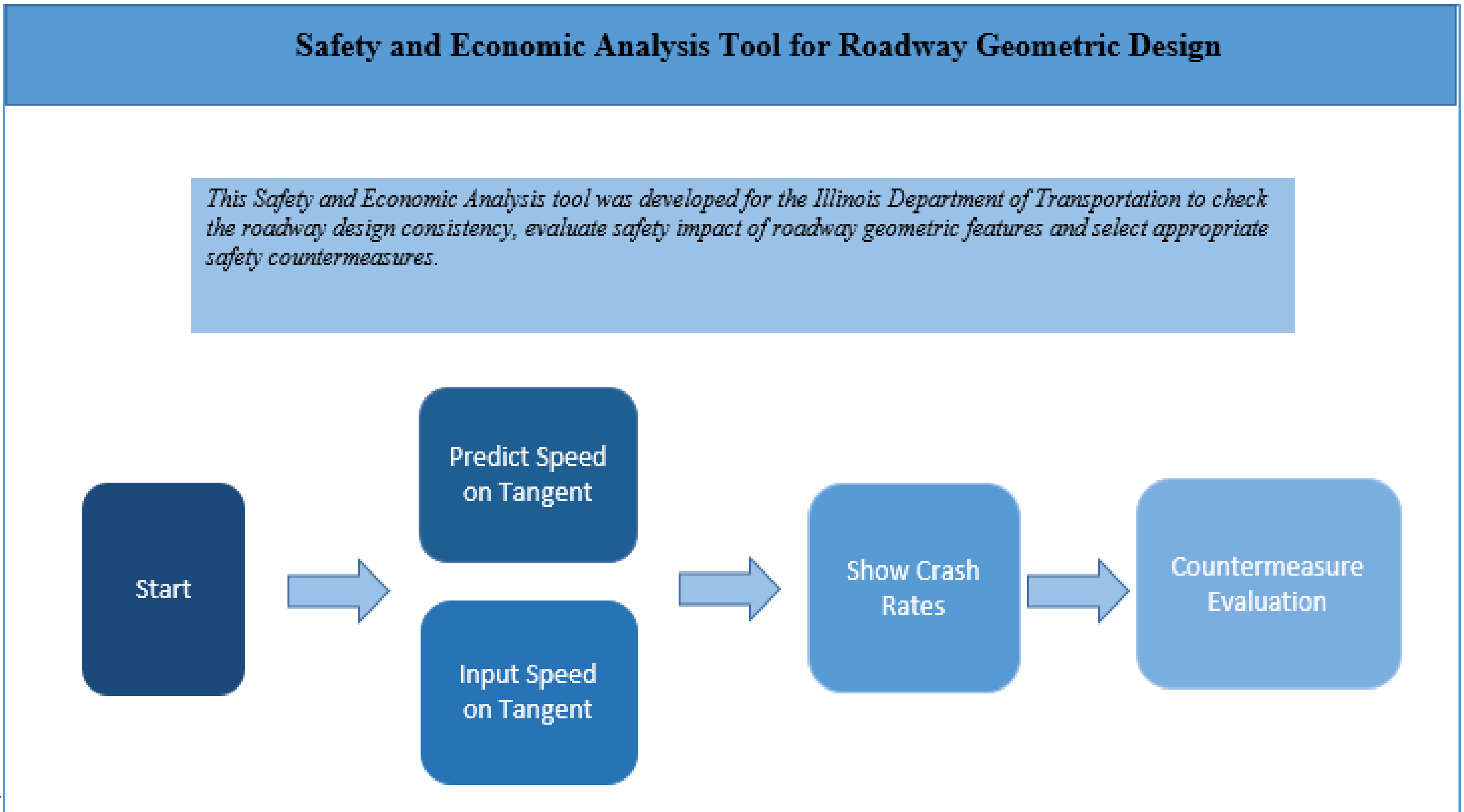
- Hypothetical 5-mile roadway section
  - 4-ft paved shoulder, 12-ft clear zone, no guardrail (cost= $39/ft), ADT = 1000 vehicles
  - Other geometric elements and costs remain the same
- Countermeasures

Case 1: 12-ft clear zone, 4-ft shoulder (benchmark)
Case 2: 16-ft clear zone, 6-ft shoulder
Case 3: 20-ft clear zone, 8-ft shoulder
Case 4: Installing guardrails (39$/ft)
Case 5: Increasing design speed to 60 mph (~ operating speed), 20-ft clear zone, 8-ft shoulder

Case	CMF	Crash Rate (Crashes/10^6 mile-veh)	Benefit $	Cost $	Benefit/Cost
1	1.026	0.11			
2	1	0.107	106,448	227,308	0.468
3	0.977	0.105	201,284	454,615	0.443
4	0.93	0.997	397,803	1,029,600	0.389
5	0.977	0.11	0	> 454,615	0

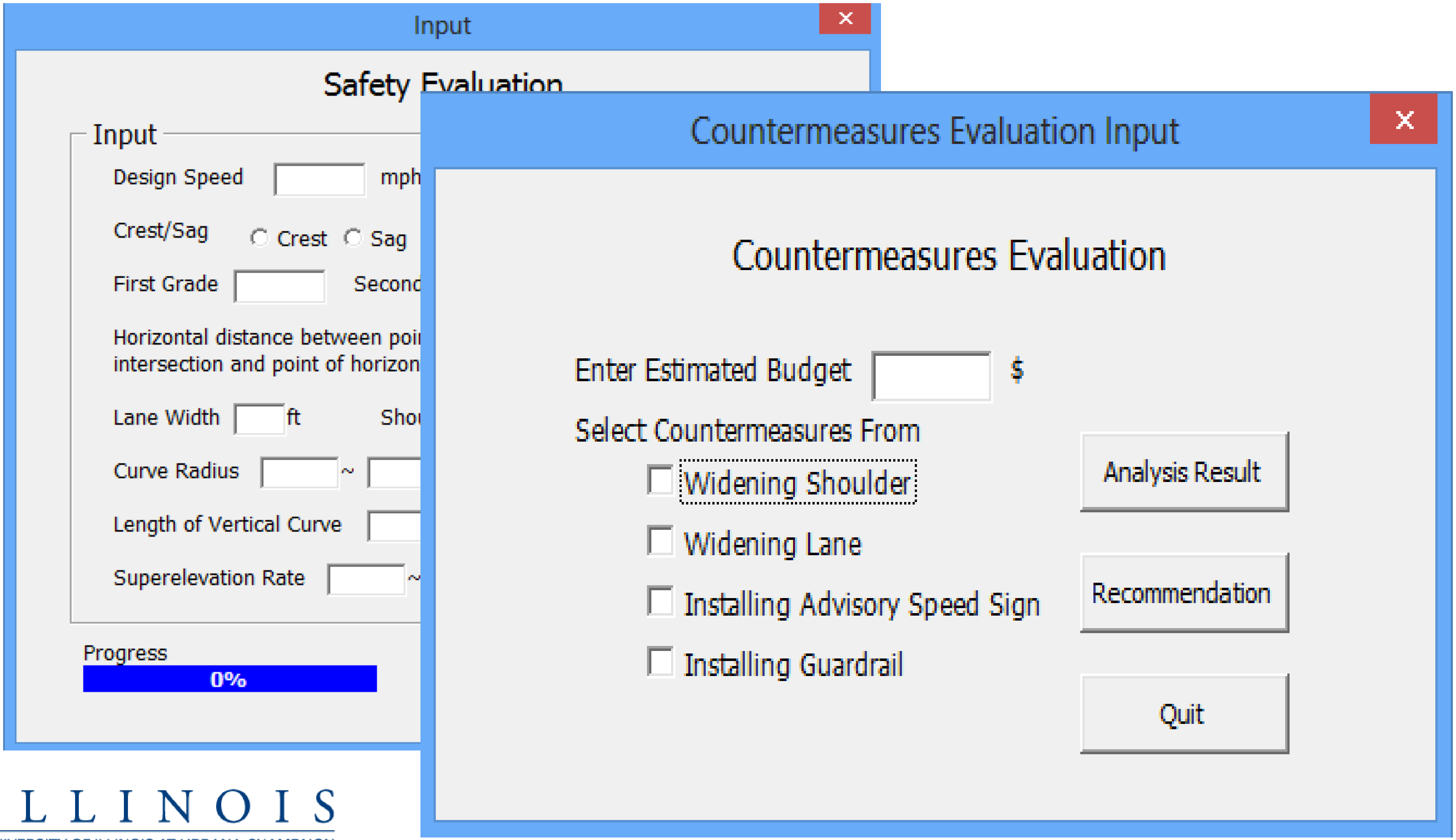
Software Development

- Excel VBA with GUI



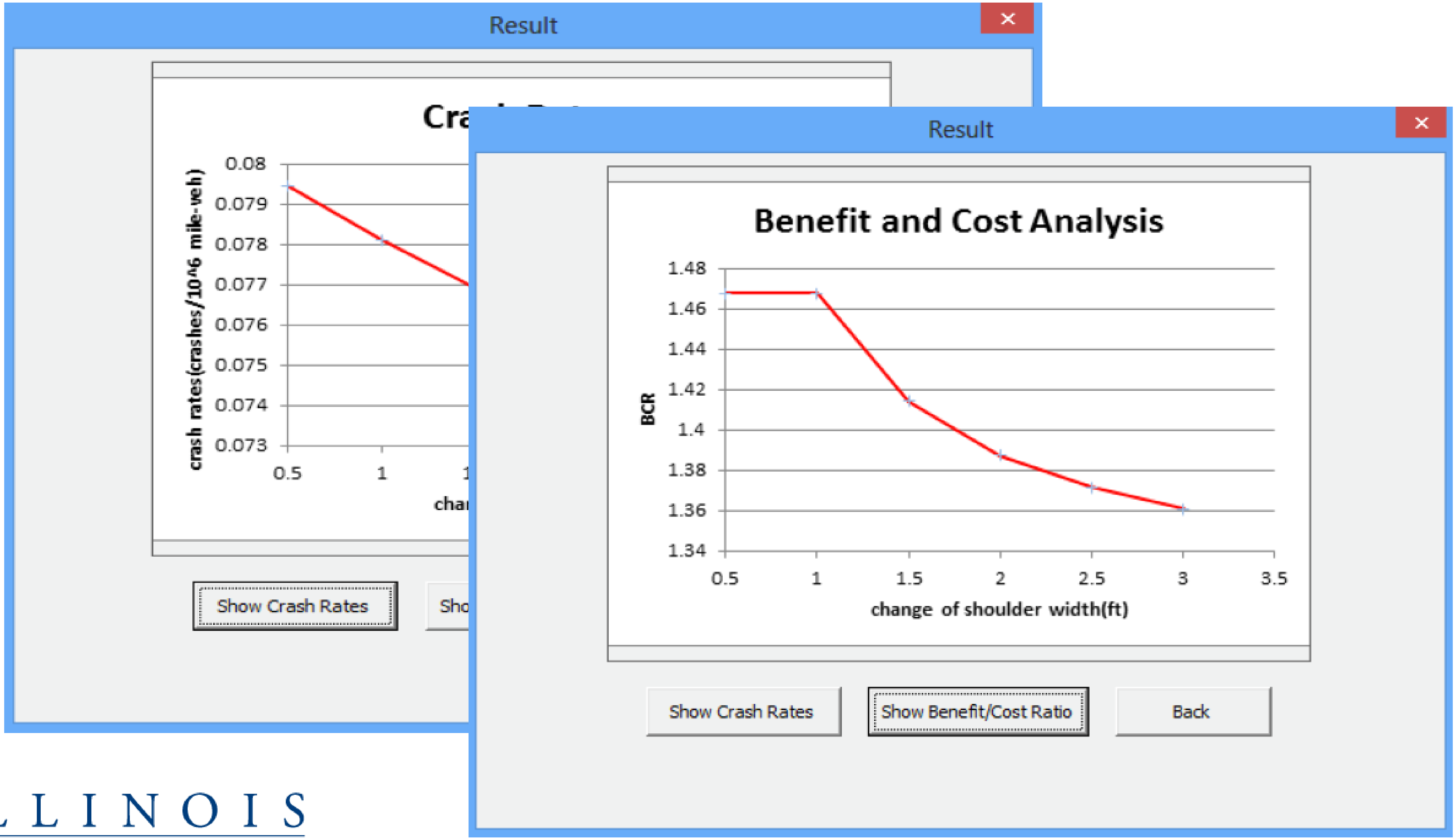
Software Development

- User Interface for Input



Software Development

- Sample Output

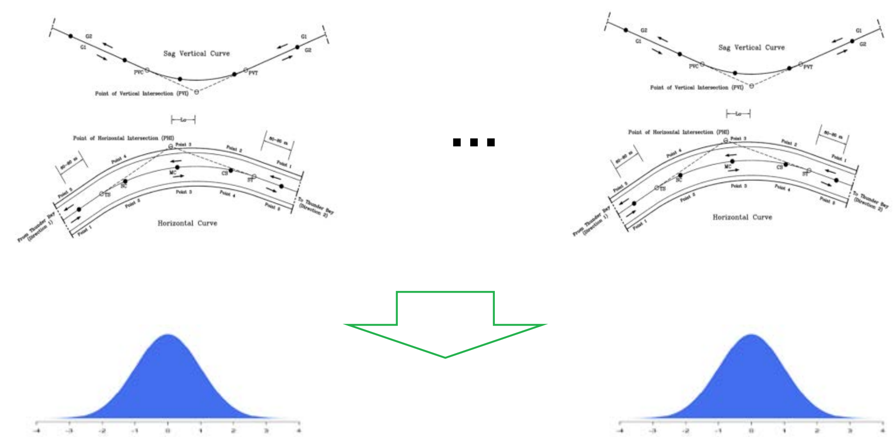


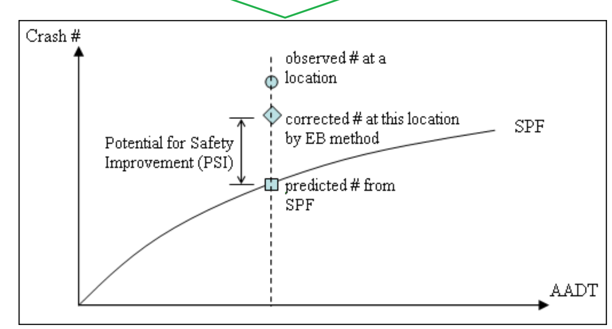
Summary

Methodology & software that

- Simulate acceptable geometric design
- Predict distribution of operating speed
- Predict crash rate
- Identify and assess safety improving countermeasures based on economic analysis
- Output: Design consistency level, crash rates, countermeasure recommendation

Design input and constraints, including design speed etc.





Identify and assess safety improving countermeasures

Thank You!

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