



A Case Study:

Smoothness Profiling in an Urban Setting

9th National Conference on
Transportation Asset Management
April 16, 2012

Pat Kennedy

Angie Hager



City and County of Denver
Public Works Street Maintenance

Outline

- Profiling / IRI Description
- Unique Urban Influences
 - Data Collection
 - Measurements
- Denver Case Study: Uses of Profiling Data
 - Before / After Repaving
 - Contracting Specifications

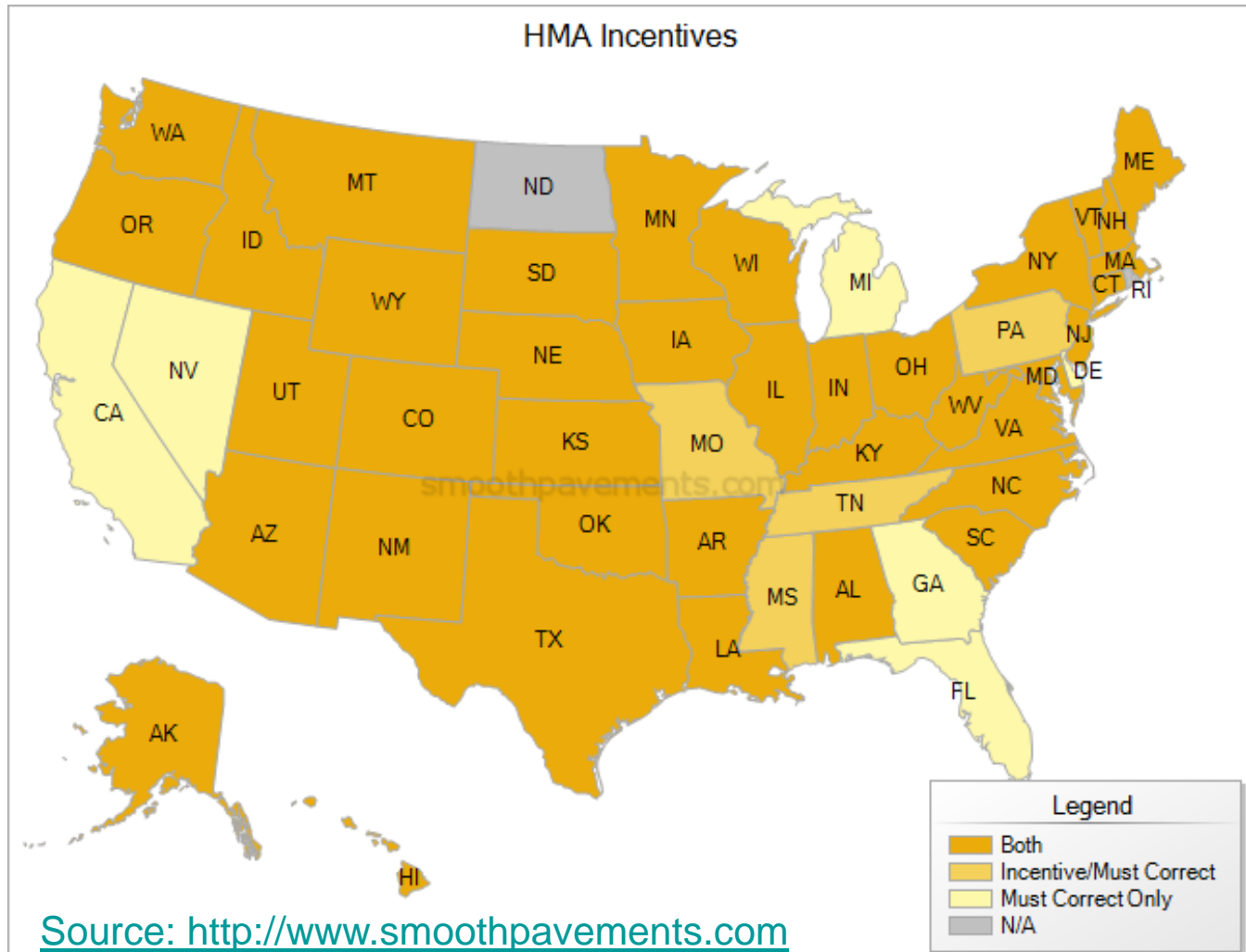
Profiling Description

- Travelling Public Perception
 - Public does not care about pavement defects that do not affect ride quality!
 - Public cares about smoothness



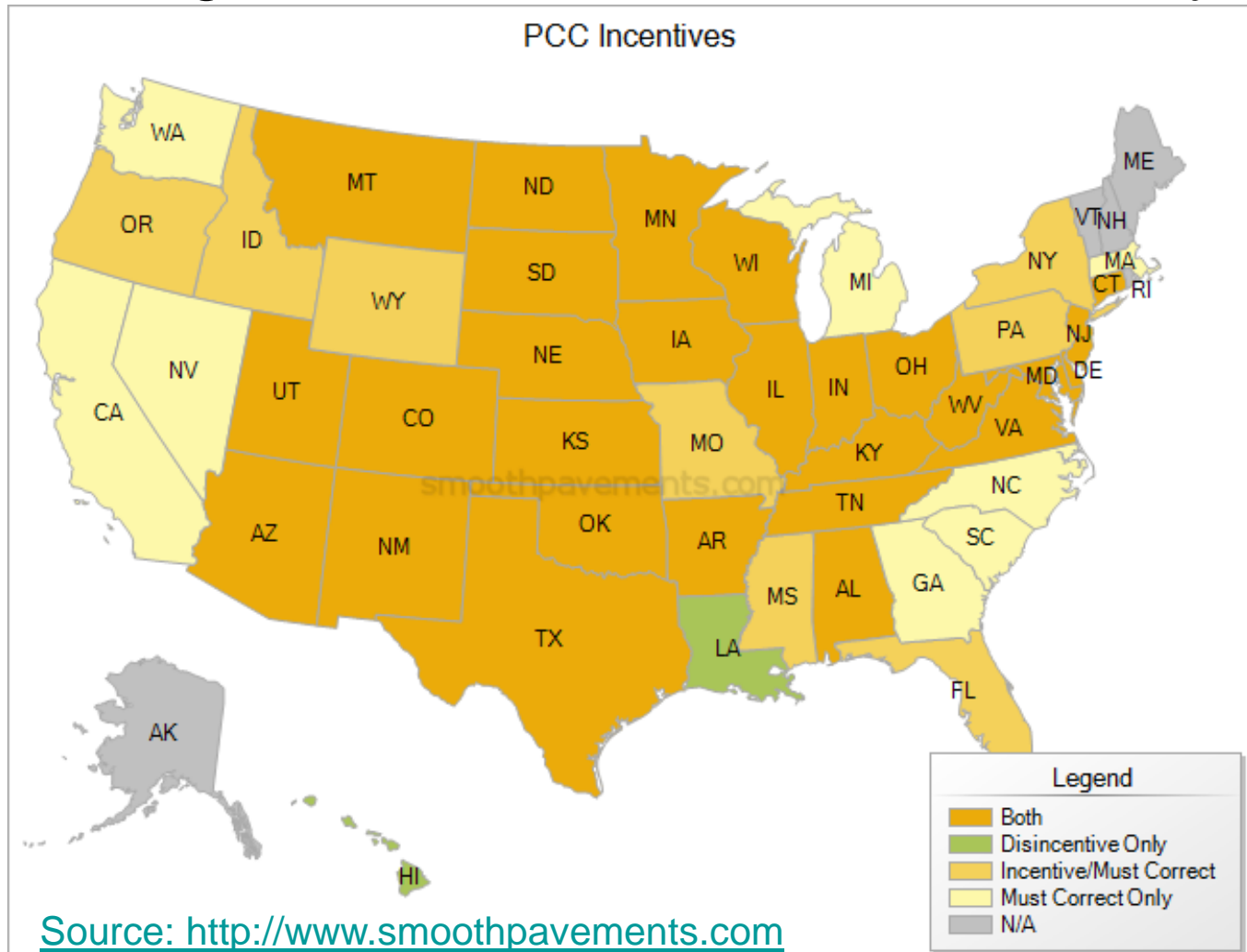
Profiling Description

Pavement Roughness Incentive/Disincentives by State



Profiling Description

Pavement Roughness Incentive/Disincentives by State



Profiling Description



International Roughness Index

- International Roughness Index (IRI)
 - Measurement Metric (in/mi, mm/km)
 - Common Use
 - Highways
 - Two-Lane Rural Roadways

Profiling Description

Alternative Profilometric Indices

- International Roughness Index (IRI)
- Half-Car Ride Index (HRI)
- Michigan Ride Quality Index (RQI)
- CalPro Simulation Model
- Straightedge / Rolling Straightedge
- The Ride Number
- The Performance Index

International Roughness Index

- Developed in 1986
- Provides a Unified Analysis Tool for Pavement Roughness
- Commonly Used in Financial Incentive/Disincentive Programs for Contractors
- Indirect Profilometric Index

International Roughness Index

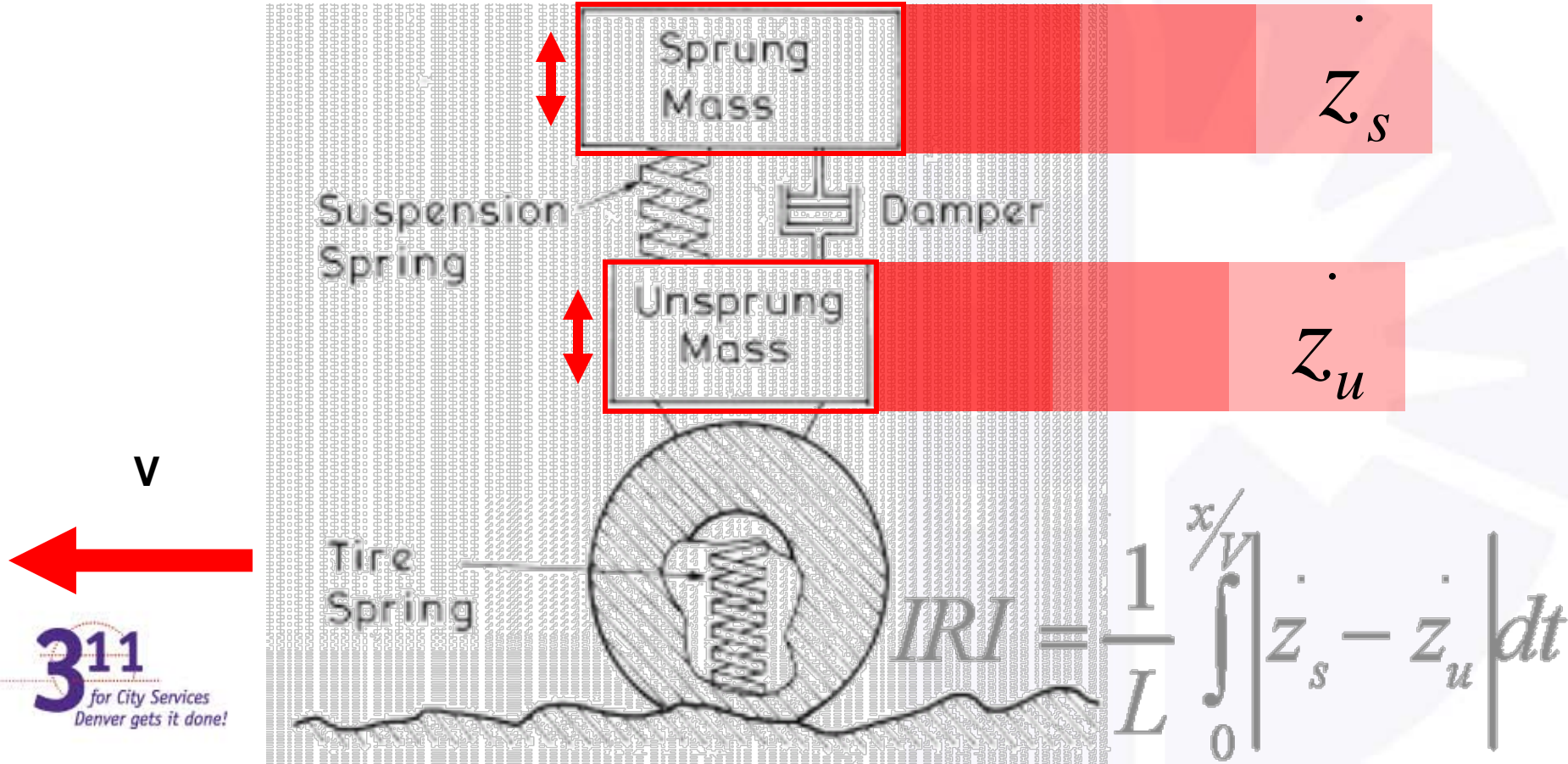
$$IRI = \frac{1}{L} \int_0^{\frac{x}{V}} \left| \dot{z}_s - \dot{z}_u \right| dt$$

Where:

IRI	=	International Roughness Index (in/mi or mm/km).
L	=	length of the section (ft or m).
V	=	speed of the quarter car model (in/sec or mm/s).
X	=	longitudinal distance of segment (in or mm).
.		
\dot{z}_u	=	vertical speed of the sprung mass in the quarter-car model diagram (in/sec).
.		
\dot{z}_s	=	vertical speed of the unsprung mass in the quarter-car model diagram (in/sec).
dt	=	the time increment (sec).

International Roughness Index

Derivation of the IRI Quarter-Car Model



International Roughness Index

Sample IRI Calculation

- Roadway Length (L): 1.0 mi
- Profiler Speed (v): 10 mi/hr = 176 in/sec
- Segment Length (x): 0.01 in
- Unsprung Mass (\dot{z}_u): 15 mi/hr = 264 in/sec
- Sprung Mass (\dot{z}_s): 25 mi/hr = 440 in/sec

$$IRI = \frac{1}{L} \int_0^{x/v} \left| \dot{z}_s - \dot{z}_u \right| dt$$

International Roughness Index

Sample IRI Calculation

$$IRI = \frac{1}{1.0 \text{ mi}} \int_0^{0.000057 \text{ sec}} \left| 440 \frac{\text{in}}{\text{sec}} - 264 \frac{\text{in}}{\text{sec}} \right| dt$$

$$1) \quad IRI = \frac{1}{1.0 \text{ mi}} \int_0^{0.000057 \text{ sec}} \left| 176 \frac{\text{in}}{\text{sec}} \right| dt$$

$$2) \quad IRI = \frac{1}{1.0 \text{ mi}} * \left[176 \frac{\text{in}}{\text{sec}} * t \right]_0^{0.000057 \text{ sec}}$$

$$3) \quad IRI = \frac{1}{1.0 \text{ mi}} * [0.01 \text{ in}]$$

$$IRI = 0.1 \text{ in/mi}$$

International Roughness Index

Literature Review

- Supporting Research on Traditional Applications of the IRI
- Standards & Practices for IRI Usage
- Concrete & Asphalt Variations in the Usage of the IRI
- IRI Applications on Urban Roadway Facilities

International Roughness Index

Research Supporting UIRI

- “Urban Considerations for Using Road Roughness to Manage Road Networks” (Reggin, Et. Al, 2008)

$$\text{Network IRI} = \frac{(\text{IRI})(L) - (1.5 \text{ m/km})(d)(n)}{(L)}$$

Where:

IRI = International Roughness Index (m/km)

L = Length of Segment (km)

d = Average Length of Railroad Crossings (km)

n = Number of Railroad Crossings in Segment

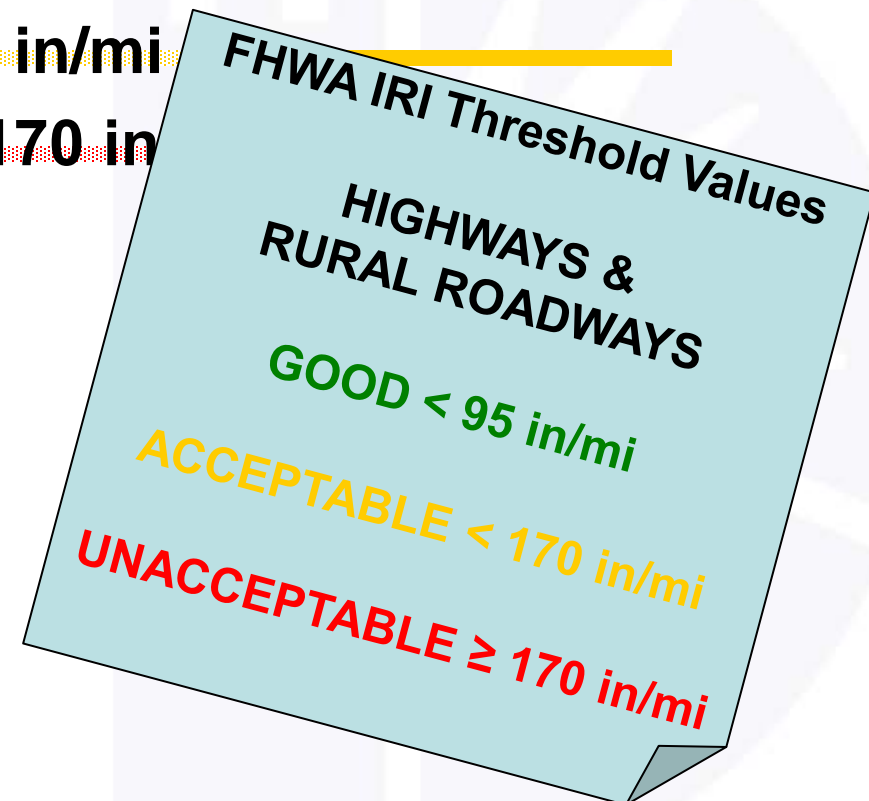
Recommended Threshold Values

FHWA Recommended IRI Threshold Values for
Highways & Rural Roadways:

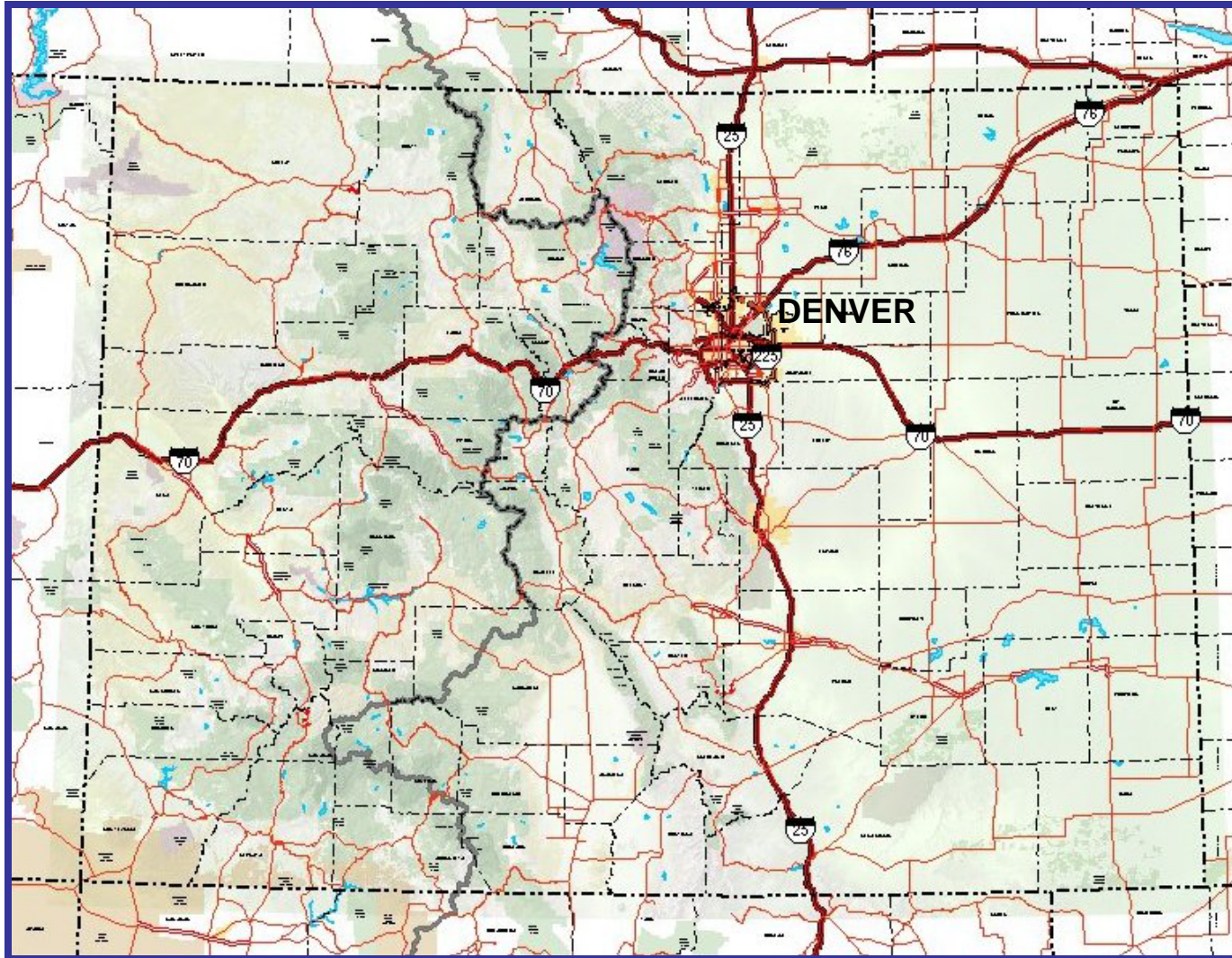
GOOD < 95 in/mi

ACCEPTABLE < 170 in/mi

UNACCEPTABLE ≥ 170 in/mi



Denver, Colorado



Urban Influences

- **Factors Influencing IRI Data Collection on Urban Roadways**
 - Traffic Signals / Stop Signs
 - Frequent Start / Stops
 - Lower Speeds



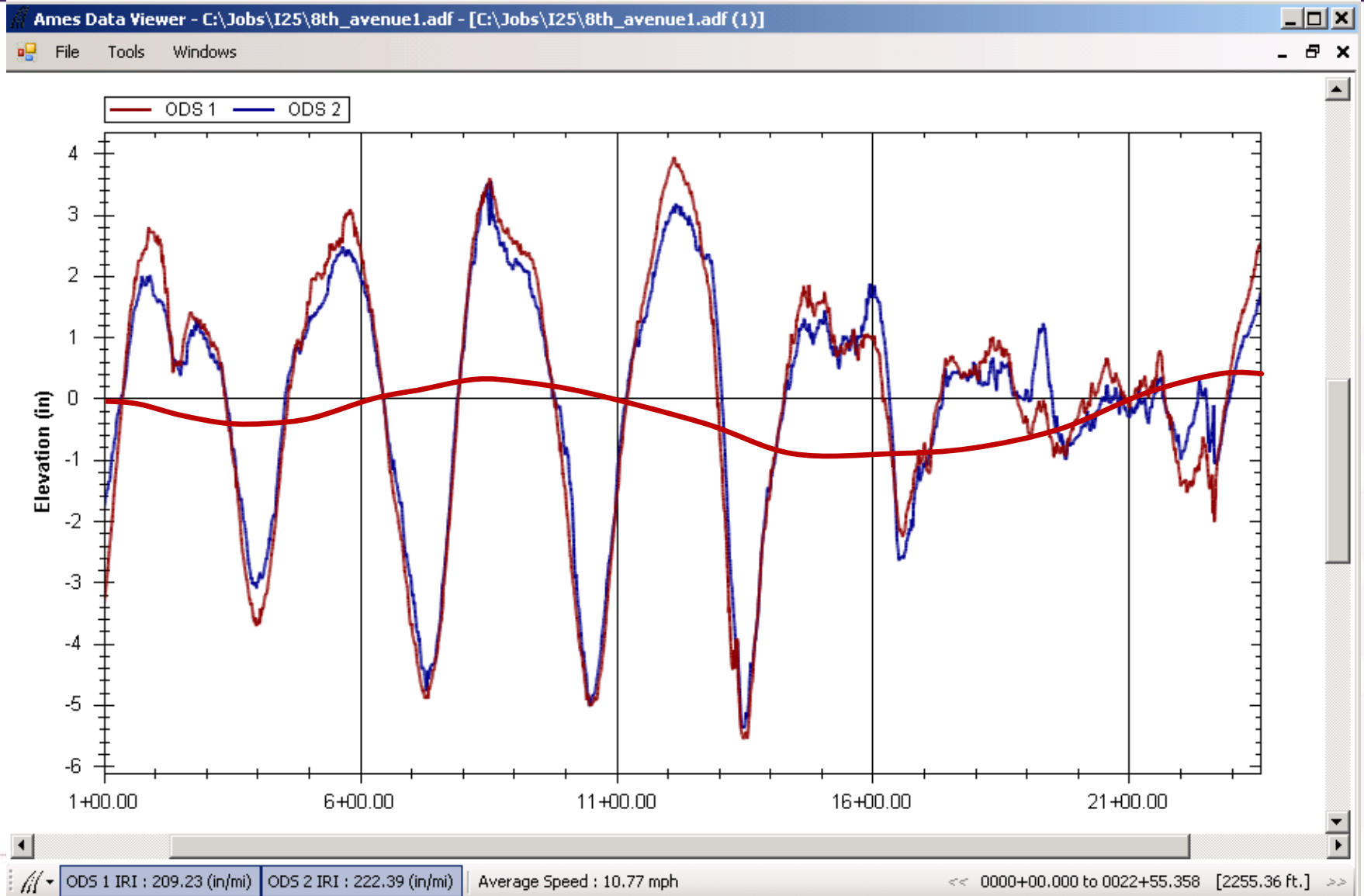
High-Speed Profiler



Low-Speed Profiler



Urban Influences



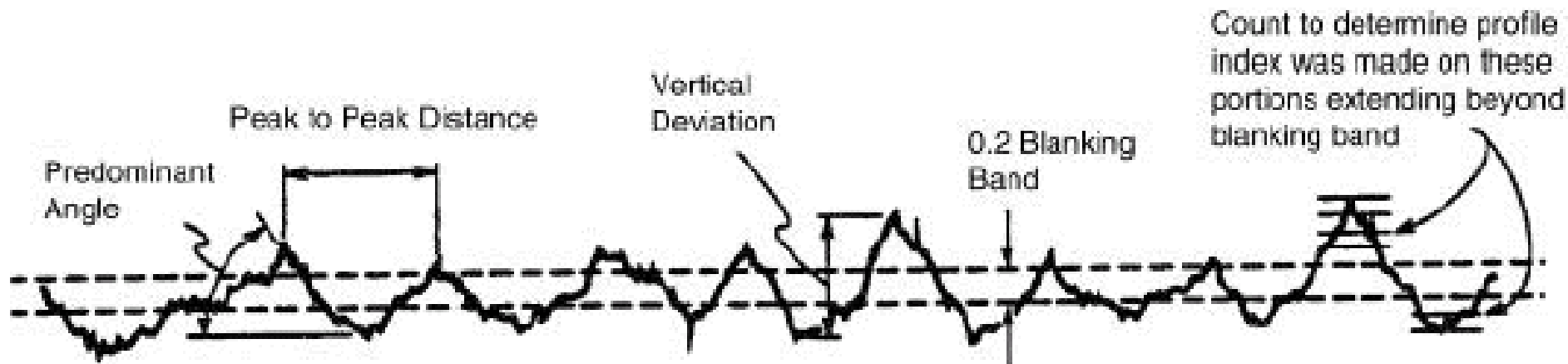
Urban Influences

- Factors Influencing **IRI Values** on Urban Roadways
 - Drainage Infrastructure
 - Cross Pans
 - Inlets
 - Utility Access Panels
 - Manhole Covers
 - Traffic Signal Panels
 - Cross Street
 - Cross-Crown Effect
 - Cross-Street Rutting
 - Other Infrastructure
 - Railroad Tracks



Urban Influences

- 2 Options to Account for Urban Influences
 - **Adjustment Factors**
 - Blanking Bands (Surface Roughness)
 - Appurtenances (Manholes, Train Tracks, etc.)
 - Intersection (Cross-crown)
 - Establish Unique Urban IRI Threshold Values



Adjustment Factors Approach

“Urban Considerations for Using Road
Roughness to Manage Road Networks”
(Reggin, Et. Al, 2008)

$$\text{Network IRI} = \frac{(\text{IRI})(L) - (1.5 \text{ m/km})(d)(n)}{(L)}$$

Where:

IRI = International Roughness Index (m/km)

L = Length of Segment (km)

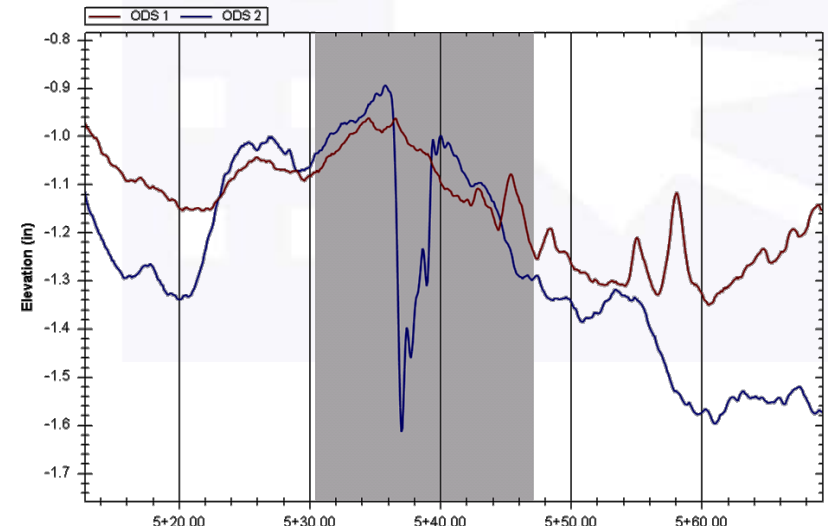
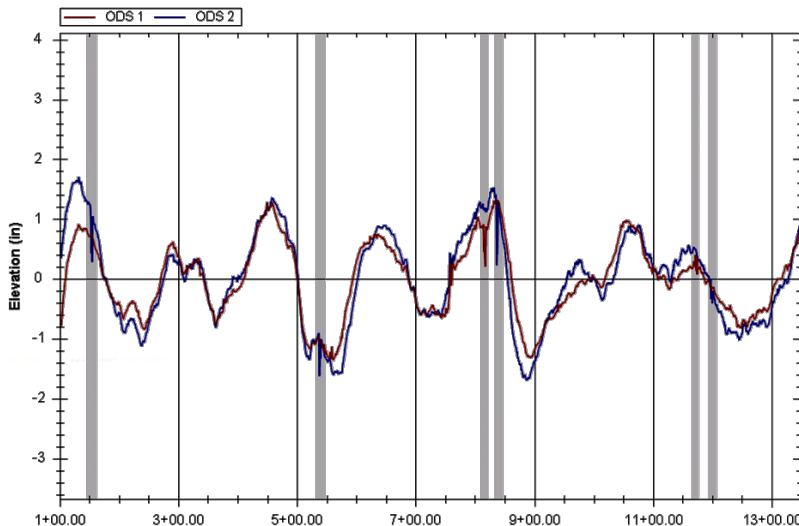
d = Average Length of Railroad Crossings (km)

n = Number of Railroad Crossings in Segment



Adjustment Factors Approach

- Infrastructure Influence
 - Elimination of Cross Street Access
 - Elimination of Manhole Covers
 - Test Site Improvement: 13%
- Ignore Function in Profiler Software



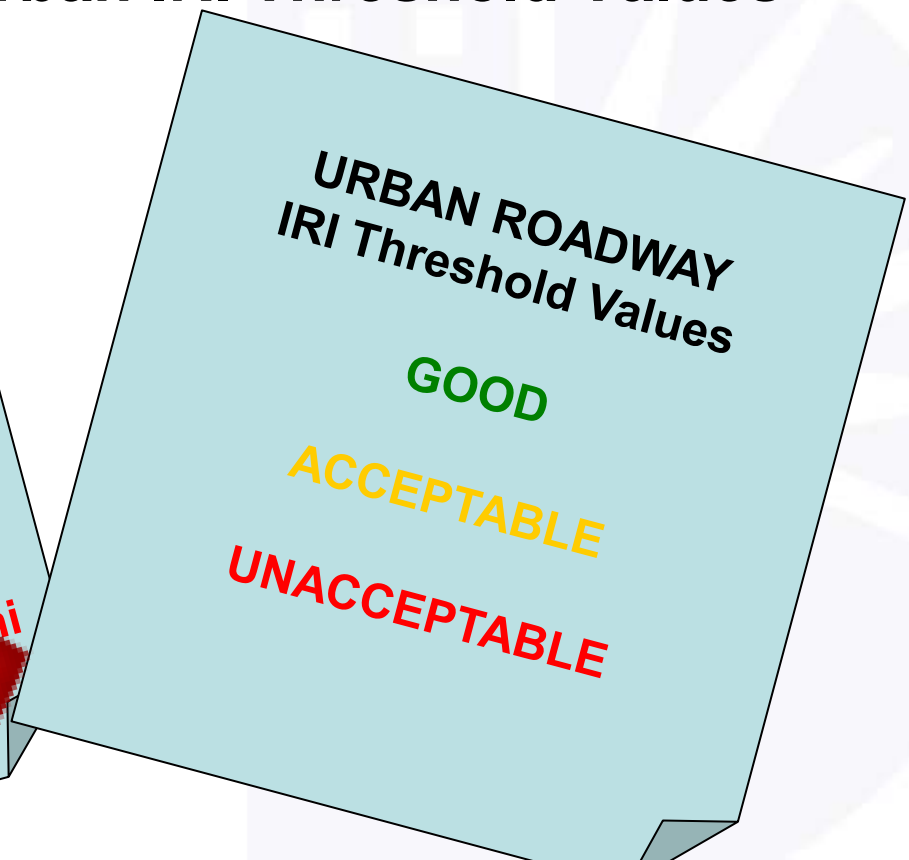


Adjustment Factors Approach

- High Pass Filter for Reducing Cross Street Impact
 - Default Setting: 0.00 ft
 - Test Setting: 70.0 ft (average cross street intersection width)
 - Average Improvement of 4-6%
- Start/Stop Condition Control For Short Segment Lengths
 - Remove First/Last 20 ft of Test Run
 - Average Improvement of 2-3%

Urban Influences

- 2 Options to Account for Urban Influences
 - Adjustment Factors
 - **Establish Unique Urban IRI Threshold Values**



Recommended Threshold Values

FHWA Recommended IRI Threshold Values for
Highways & Rural Roadways

**HIGHWAYS &
RURAL ROADWAYS**

GOOD < 95 in/mi

ACCEPTABLE < 170 in/mi

UNACCEPTABLE ≥ 170 in/mi

**URBAN
ROADWAYS**

GOOD < 150 in/mi

ACCEPTABLE < 220 in/mi

UNACCEPTABLE ≥ 220 in/mi

ACCEPTABLE < 220 in/mi

UNACCEPTABLE ≥ 220 in/mi



Case Study: Denver Profiling

- Equipment
- Repeatability Study
- Before and After Repaving
 - % Improvement
 - By Pavement Treatment
 - Established UIRI Threshold Value
- Contract Specifications
 - DTC Blvd
 - Martin Luther King Parkway

Case Study: Denver Profiling

- Low Speed Pavement Profiler
 - Laser Inertial Surface Analyzer (LISA) 6500 Pavement Profiler by Ames Engineering
 - Dual Laser Track
- Lead & Lag Vehicle For Safety
- Four-Person Data Collection Teams (3 drivers, 1 operator)





- Pro Eng
- Pro Styl

Setup

Report Options Analysis Setup Profiler Setup

Reduction Settings

Reduction Length feet

Short Segment Length feet

☐ Static Reduction Segments

Bump Detection Settings

Bump Width feet

Bump Height inches

☒ Bump Detection Enabled

☒ Dip Detection Enabled

Filter Settings

High Pass Filter Cutoff feet

Low Pass Filter Cutoff feet

☐ Moving Average Filter Enabled

☒ Debris Filter Enabled

Rolling Straightedge Simulation

Straightedge Length feet

Specification Limit inches

CalPro Simulation

Blanking Band Width inches

Minimum Scallop Height inches

Minimum Scallop Width feet

Scallop Rounding inches

☒ Count Scallops Once

Units

☒ English ☐ Metric

Save Cancel

C:\Documents and Settings\All Users\Application Data\AmesPro\Setup.xml

From

1+00

6+28

11+56

16+84

Total

From

1+00

6+28

11+56

16+84

Total

From

1+00

6+28

11+56

16+84

Total

Dip 9+44 9+51 9+53

Bump 9+89 9+90 9+98

Dip 10+10 10+10 10+10

Bump 10+27 10+33 10+43

nin 11+66 11+67 11+73

Height (in)

0.29

0.07

0.07

0.04

0.21

0.43

0.06

0.03

0.23

0.27

0.05

0.16

0.59

0.08

0.57

0.18

0.09

0.72

Height (in)

0.14

0.01

0.09

0.16

0.20

0.08

0.02

0.04

0.13

0.10

0.03

0.39

0.11

ES

Ames Engineering Profiler Software

AMES ENGINEERING

Profile 1 Profile 2 Switch Pod

Height --- in

Status

GPS

Latitude

Longitude

Speed

Link Quality No Connection

System

Cycle Count 3

Battery Voltage --- V

System Status Connection Error

Time/Date

10:22:03 AM

Thursday, April 07, 2009

P1 - Setup P2 - Calibrate P3 - Start P5 - Analyze P6 - View P10 - Quit

Start

Analyze

Calibrate

Setup

View

Quit

Setup

Report Options Analysis Setup Profiler Setup

Reduction Settings

Reduction Length feet

Short Segment Length feet

☐ Static Reduction Segments

Bump Detection Settings

Bump Width feet

Bump Height inches

☒ Bump Detection Enabled

☒ Dip Detection Enabled

Filter Settings

High Pass Filter Cutoff feet

Low Pass Filter Cutoff feet

☐ Moving Average Filter Enabled

☒ Debris Filter Enabled

Rolling Straightedge Simulation

Straightedge Length feet

Specification Limit inches

CalPro Simulation

Blanking Band Width inches

Minimum Scallop Height inches

Minimum Scallop Width feet

Scallop Rounding inches

☒ Count Scallops Once

Units

☒ English ☐ Metric

Save Cancel

C:\Documents and Settings\All Users\Application Data\AmesPro\Setup.xml

From	To	Dist	IRI (in/mi)	RN
1+00	6+28	528	213.42	1.90
6+28	11+56	528	211.53	2.51
11+56	16+84	528	171.59	2.76
16+84	17+96	112	437.86	1.12
Total		1696	214.63	2.31

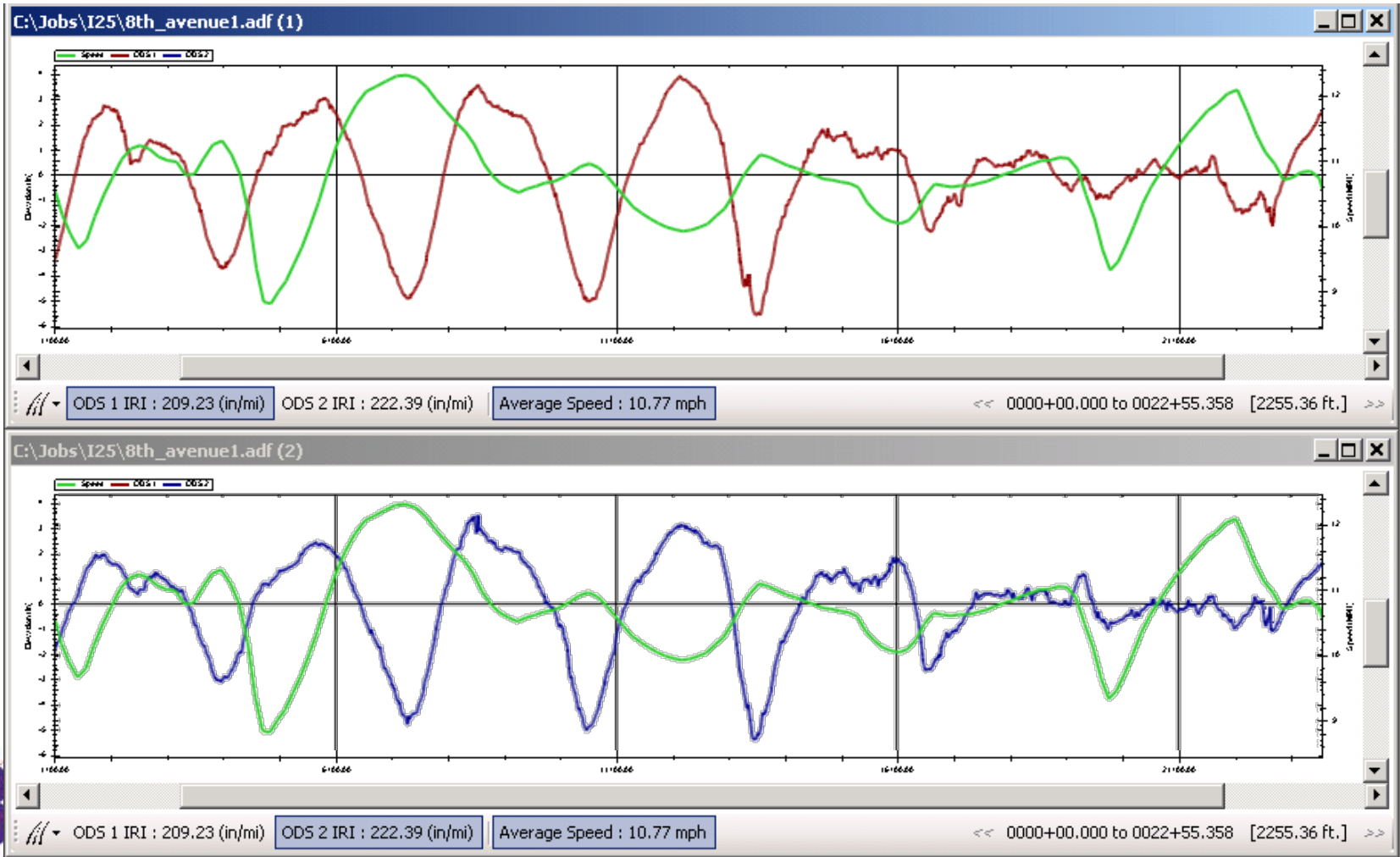
From	To	Dist	IRI (in/mi)	RN
1+00	6+28	528	170.57	2.50
6+28	11+56	528	203.99	2.63
11+56	16+84	528	204.83	2.15
16+84	17+96	112	580.51	0.59
Total		1696	218.71	2.25

From	To	Dist	Summary Average	IRI (in/mi)	RN
1+00	6+28	528	192.00	2.10	
6+28	11+56	528	207.76	2.57	
11+56	16+84	528	188.21	2.46	
16+84	17+96	112	509.18	0.86	
Total		1696	216.67	2.28	

Type	Bump/Dip	Locations	Track 1	Track 2	Height (in)
	From	Peak	To	To	
Dip	1+17	1+18	1+19	0.29	
Dip	2+97	2+97	2+98	0.07	
Bump	2+98	2+99	3+00	0.07	
Bump	3+03	3+03	3+04	0.04	
Dip	3+07	3+08	4+01	0.21	
Bump	4+13	4+23	4+30	0.43	
Dip	4+37	4+38	4+39	0.06	
Dip	5+41	5+41	5+41	0.03	
Bump	7+74	7+79	7+89	0.23	
Dip	8+10	8+18	8+24	0.27	
Bump	8+91	8+92	8+92	0.05	
Bump	9+58	9+90	10+01	0.16	
Dip	10+01	10+06	10+15	0.59	
Bump	10+21	10+29	10+31	0.08	
Dip	13+03	13+13	13+23	0.57	
Bump	15+96	16+02	16+06	0.18	
Dip	17+38	17+41	17+44	0.09	
Bump	17+59	17+61	17+75	0.72	

Type	Bump/Dip	Locations	Track 2	Track 2	Height (in)
	From	Peak	To	To	
Bump	4+16	4+24	4+20	0.14	
Dip	4+75	4+75	4+75	0.01	
Dip	6+52	6+56	6+70	0.09	
Bump	6+77	6+81	6+87	0.16	
Dip	8+23	8+25	8+33	0.08	
Bump	8+42	8+42	8+42	0.02	
Bump	9+05	9+06	9+07	0.04	
Dip	9+44	9+51	9+53	0.13	
Bump	9+89	9+90	9+98	0.10	
Dip	10+10	10+10	10+10	0.03	
Dip	10+27	10+33	10+43	0.39	
Bump	11+66	11+67	11+73	0.11	

Profiler Software



Project Scope

- Test Sites Spanned 66.9 Lane Miles in the CCD (134 segments)
 - **55.4 mi of Before Repaving Condition** (79 segments)
 - **39.3 mi of After Repaving Condition** (55 segments)
 - **27.15 mi of Both Before & After Condition** (33 segments)
 - Average Segment Length: 0.69 mi

Repeatability Study

- Minimum of Two Drivers Used on All Data Collection Directions
- Examined Sites for Collection
 - Five IRI Measurements were Examined, Percent Difference Values Were Derived and Averaged:

Average IRI		Difference
(in/mi)	(mm/km)	
237.42	3747.182	1.1%
182.57	2881.489	2.1%

Street	From / To		Segment Length		Track	Driver 1		Driver 2		Driver 3		Driver 4		Driver 5		Average IRI		Difference
			(mi)	(km)	Track	(in/mi)	(mm/km)	(in/mi)	(mm/km)	(in/mi)	(mm/km)	(in/mi)	(mm/km)	(in/mi)	(mm/km)	(in/mi)	(mm/km)	
E. 8th Ave.	Steele St.	Harrison St.	0.40	0.64	ODS1	232.50	3669.53	231.67	3656.43	227.62	3592.51	219.06	3457.41	238.81	3769.12	237.42	3747.182	1.1%
					ODS2	247.00	3898.38	236.48	3732.35	242.11	3821.20	260.11	4105.30	238.81	3769.12			
					AVG	239.75	3783.96	234.08	3694.39	234.87	3706.86	239.59	3781.35	238.81	3769.12			
E. 8th Ave.	Downing St.	York St.	0.68	1.09	ODS1	154.33	2435.78	162.73	2568.36	163.77	2584.77	162.34	2562.20	159.38	2515.48	182.57	2881.489	2.1%
					ODS2	200.69	3167.48	210.35	3319.94	206.46	3258.54	197.28	3113.66	208.42	3289.48			
					AVG	177.51	2801.63	186.54	2944.15	185.12	2921.66	179.81	2837.93	183.90	2902.48			

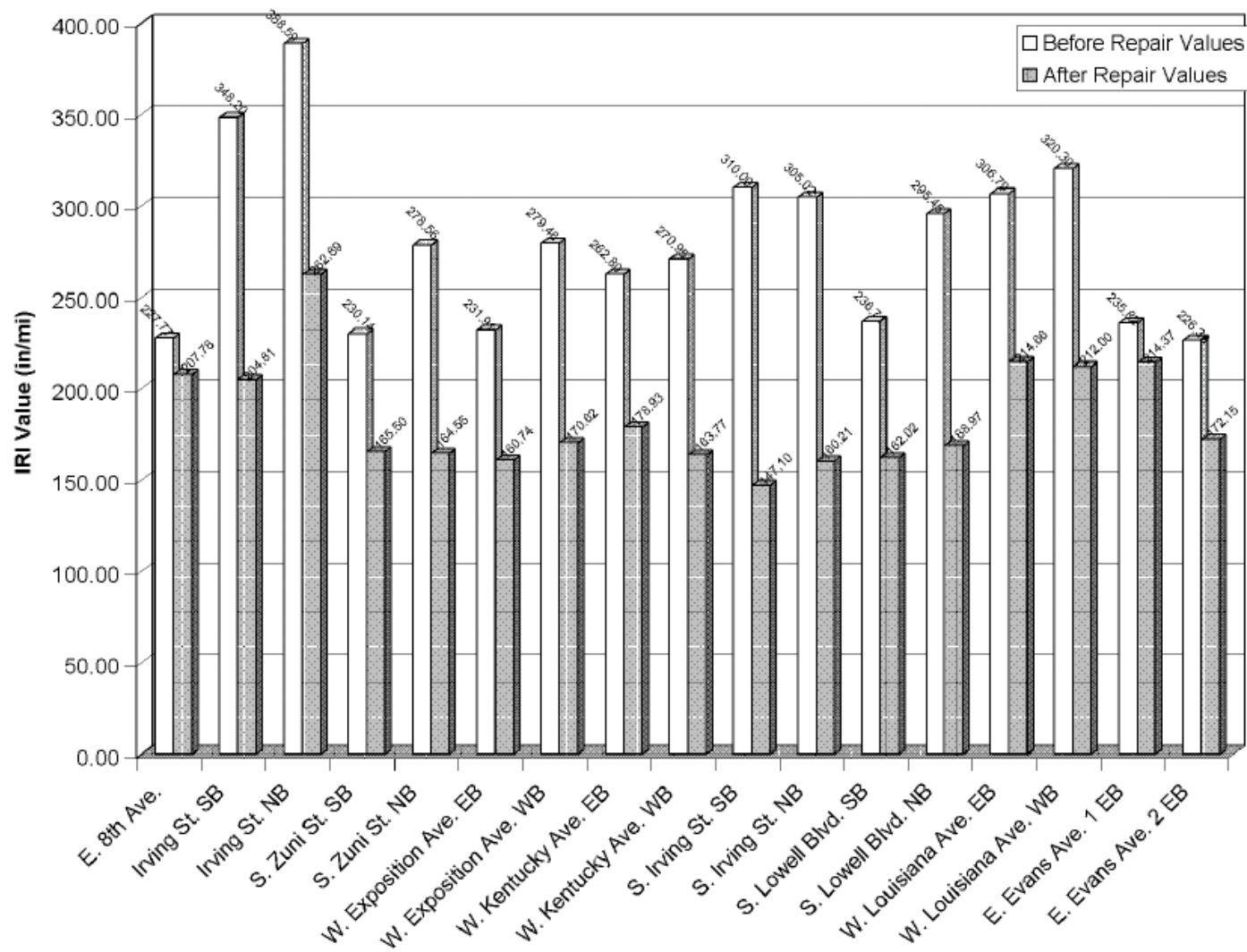
Before & After Study

- Study included 27.15 mi (33 segments) of Data Collected both Before & After Repaving
- Data Collection Planned as Close to the Repaving Date as Possible
- Infrastructure Conditions Varied Widely by Site

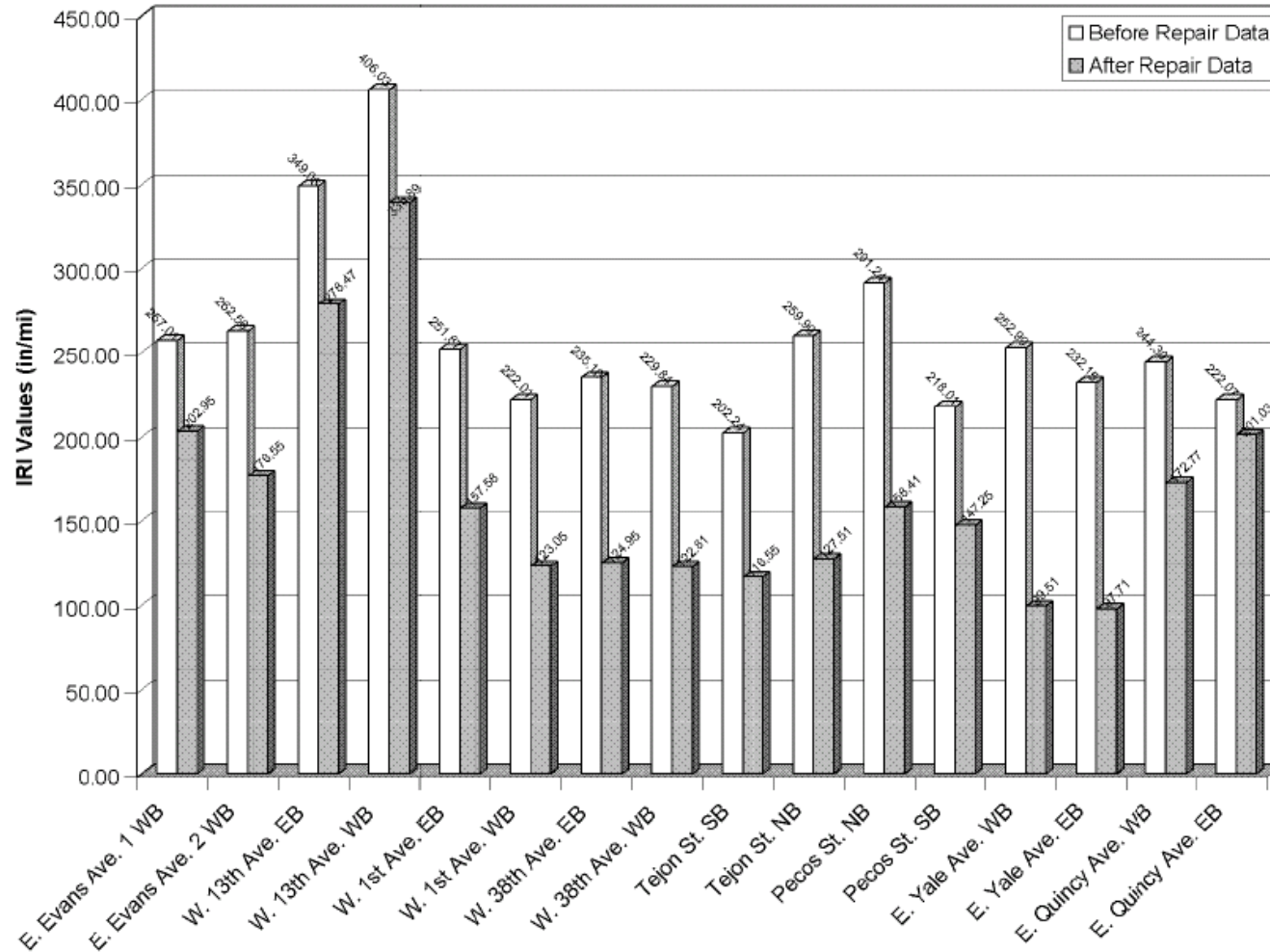
Before & After Study

- Average IRI Values Weighted by Segment Length:
 - Before Repaving: 375.28 in/mi (5922.97 mm/km)
 - After Repaving: 170.53 in/mi (2691.44 mm/km)
 - Percent Improvement: 36.3%

Before & After Study



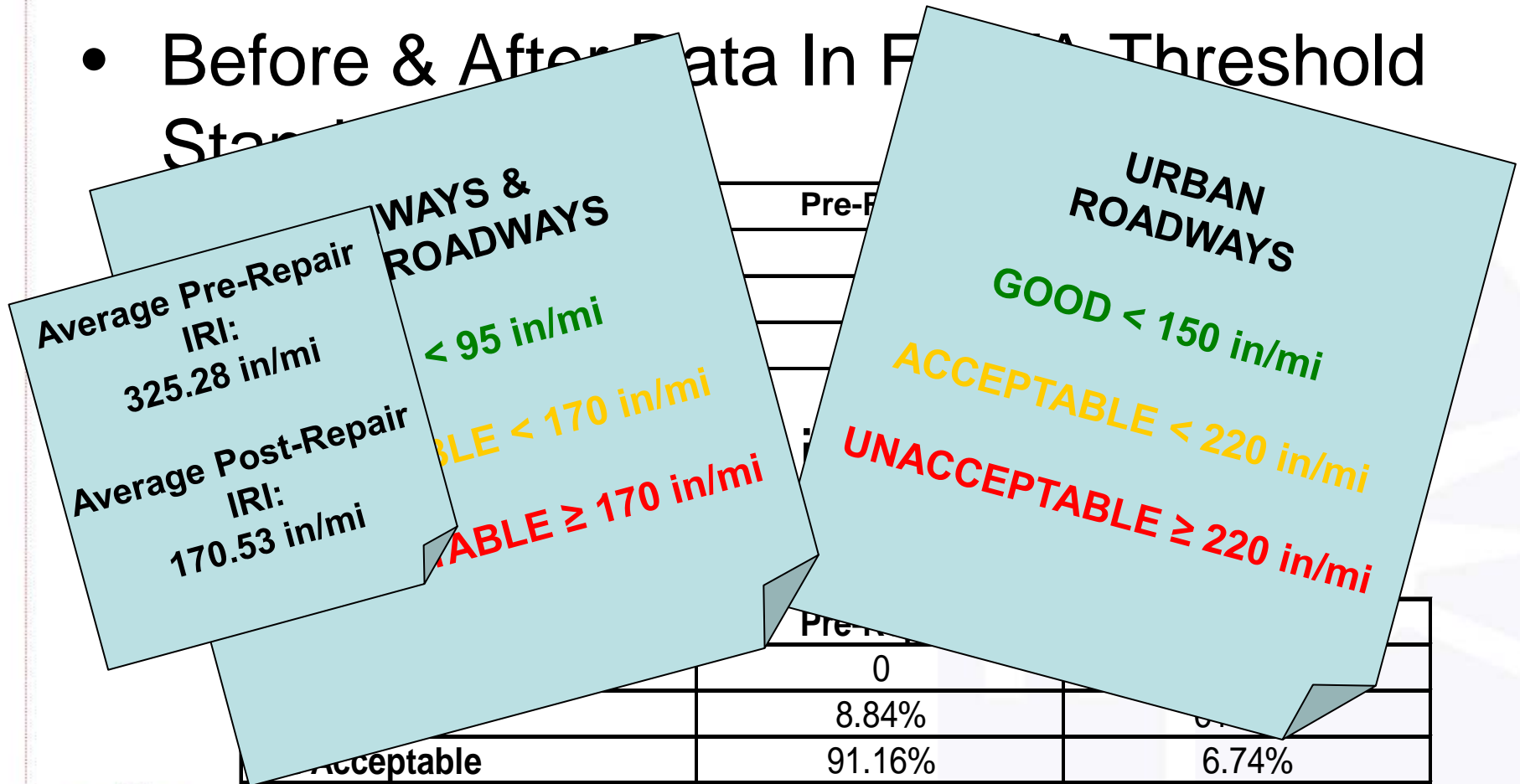
Before & After Study



UIRI

Threshold Values

- Before & After Data In F... Threshold



Repaving Methods Used

- Mill & Overlay (M&O)
 - Road is milled (up to a depth of 3 in.)
 - New asphalt is placed atop milled surface.
- Hot In Place Recycling (HIPR)
 - Outer edges of the street are milled (up to 1.5 in.)
 - Existing pavement is heated and scarified
 - Mix of new asphalt, existing asphalt and reconstituting agent is placed.
- Complete Reconstruction
 - Complete removal of existing asphalt
 - Placement of new asphalt



Repaving Method Comparison Study

- Total After Repaving Condition Sites Include 39.3 mi (55 segments)
 - M&O: 27.61 mi (39 segments)
 - HIPR: 9.16 mi (8 segments)
 - Reconstruct: 4.12 mi (8 segments)
- Before & After Repaving Condition Sites Include 27.15 mi (33 segments)
 - M&O: 16.71 mi (21 segments)
 - HIPR: 9.16 mi (8 segments)
 - Reconstruct: 1.28 mi (4 segments)

Repaving Method Comparison Study

- After Repaving Condition:

Resurfacing Method	Total Length Tested (mi) / (km)		Number of Segments Tested	Weighted Average IRI (in/mi) / (mm/km)	
Mill & Overlay	27.61	44.43	39	188.85	2980.58
HIPR	9.16	14.74	8	128.47	2027.62
Reconstruction	2.56	4.12	8	202.16	3190.65

- Before & After Repaving Condition:

Resurfacing Method	Before Repaving Condition					Percent Improvement
	Length Tested (mi) / (km)	Number of Segments Tested	Weighted Average IRI (in/mi) / (mm/km)		After Repaving Weighted Average IRI (in/mi) / (mm/km)	
Mill & Overlay	26.89	21	280.27	4423.45	190.06	32.2%
	14.74	8	240.55	3796.55	128.48	
	2.06	4	300.65	4745.10	216.61	
HIPR						46.6%
Reconstruction						28.0%



Contract Specs

DTC Blvd

- DTC Blvd from I-225 to Belleview Ave
 - Approx 0.7 mi. centerline length (27,500 SY)
 - Divided Roadway
 - Concrete Pavement
 - Arterial
- 30% Improvement Contracted



Contract Specs

DTC Blvd



Contract Specs

DTC Blvd

- Fixing drainage



Contract Specs

DTC Blvd

- Full Panel Replacement



Contract Specs

DTC Blvd

- Patching



Contract Specs

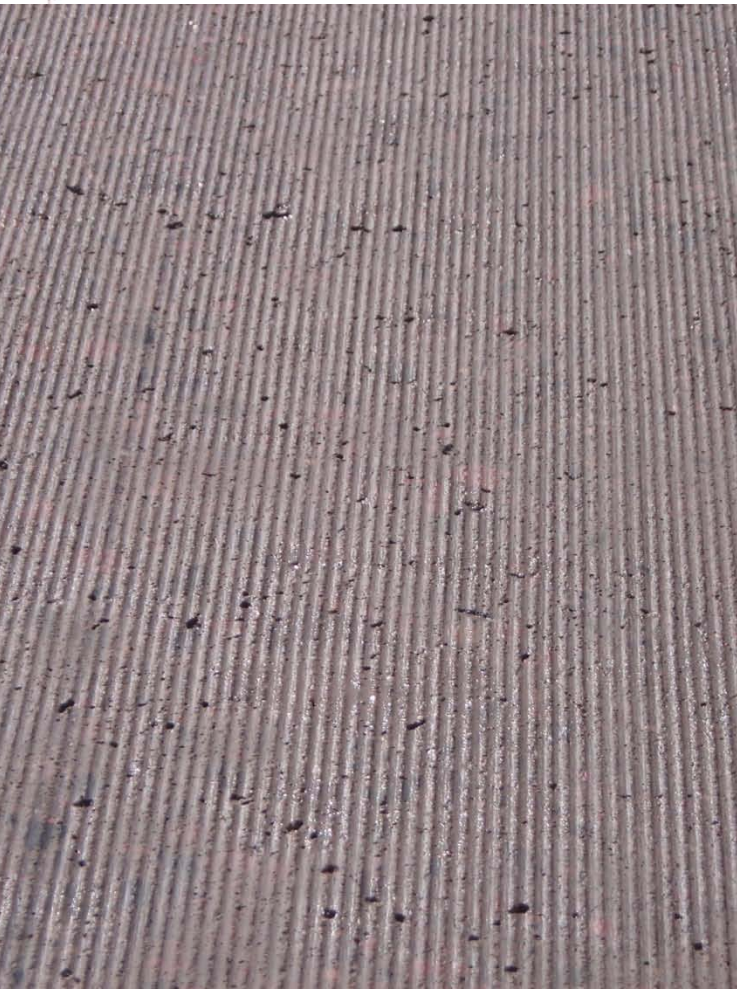
DTC Blvd

- Sawing and Sealing



Contract Specs DTC Blvd

- Grinding





Contract Specs DTC Blvd

- Profiling
 - Contracted: 30% Improvement
 - Achieved: 32% Improvement





Contract Specs

MLK Blvd

- Martin Luther King Blvd from Colorado Blvd to Quebec
 - Approx 2 miles
 - Divided Roadway
 - Concrete Pavement
 - Arterial
- 25% Improvement Contracted



Contract Specs MLK Blvd

Intersection reconstruction



Contract Specs

MLK Blvd

- Full Panel Replacement



Contract Specs MLK Blvd

- Partial Depth Repair



Contract Specs MLK Blvd

- Profiling
 - Contracted: 25% Improvement
 - Achieved: 14% Improvement
- ACPA CO/WY Regional Award
- ACPA National Gold Medal Award



Conclusion Statements

- IRI is a valuable tool
- Awareness of Influences
- Contractual Provisions
 - % Improvement
 - Target IRI

Acknowledgements

University of Colorado Denver

- Brian J. Staley
- Dr. Kevin L. Rens

City and County of Denver

- Pat Kennedy
- Brian Roecker
- Angie Hager
- Lindsey VanCleave
- Clayton Goodwin



Questions?



Pat Kennedy, PE
Engineering Supervisor
Denver Street Maintenance
(303) 446-3535
william.kennedy@denvergov.org

Angela Hager, PE, PhD
Engineer
Denver Street Maintenance
(303) 446-3534
angela.hager@denvergov.org