U.S. Department of Transportation
Federal Highway Administration

Quantifying Environmental Impacts of Pavements

RPUG
24th Annual Meeting

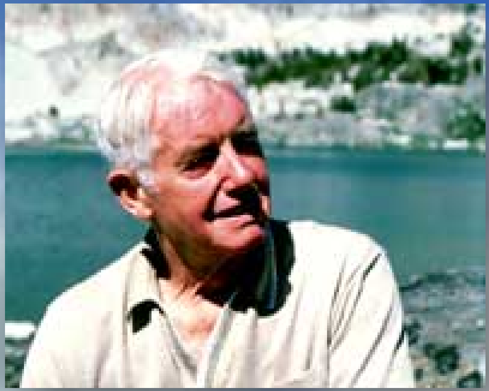
Thomas Harman
Manager, FHWA Pavement & Materials TST
Baltimore, MD

Preamble

David Brower,

“We do not inherit the land from our fathers, we borrow it from our children.”

The environment is very important!



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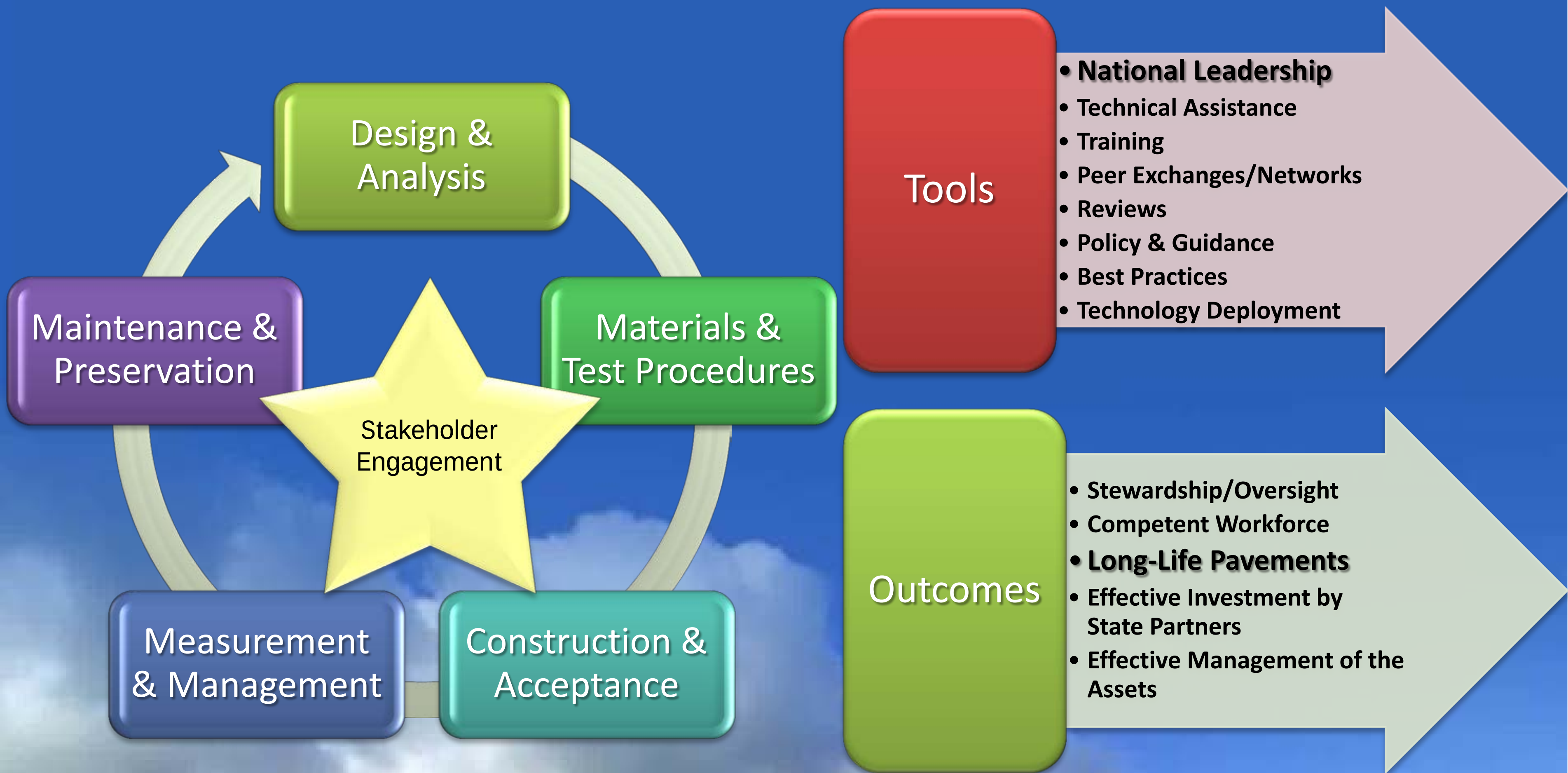
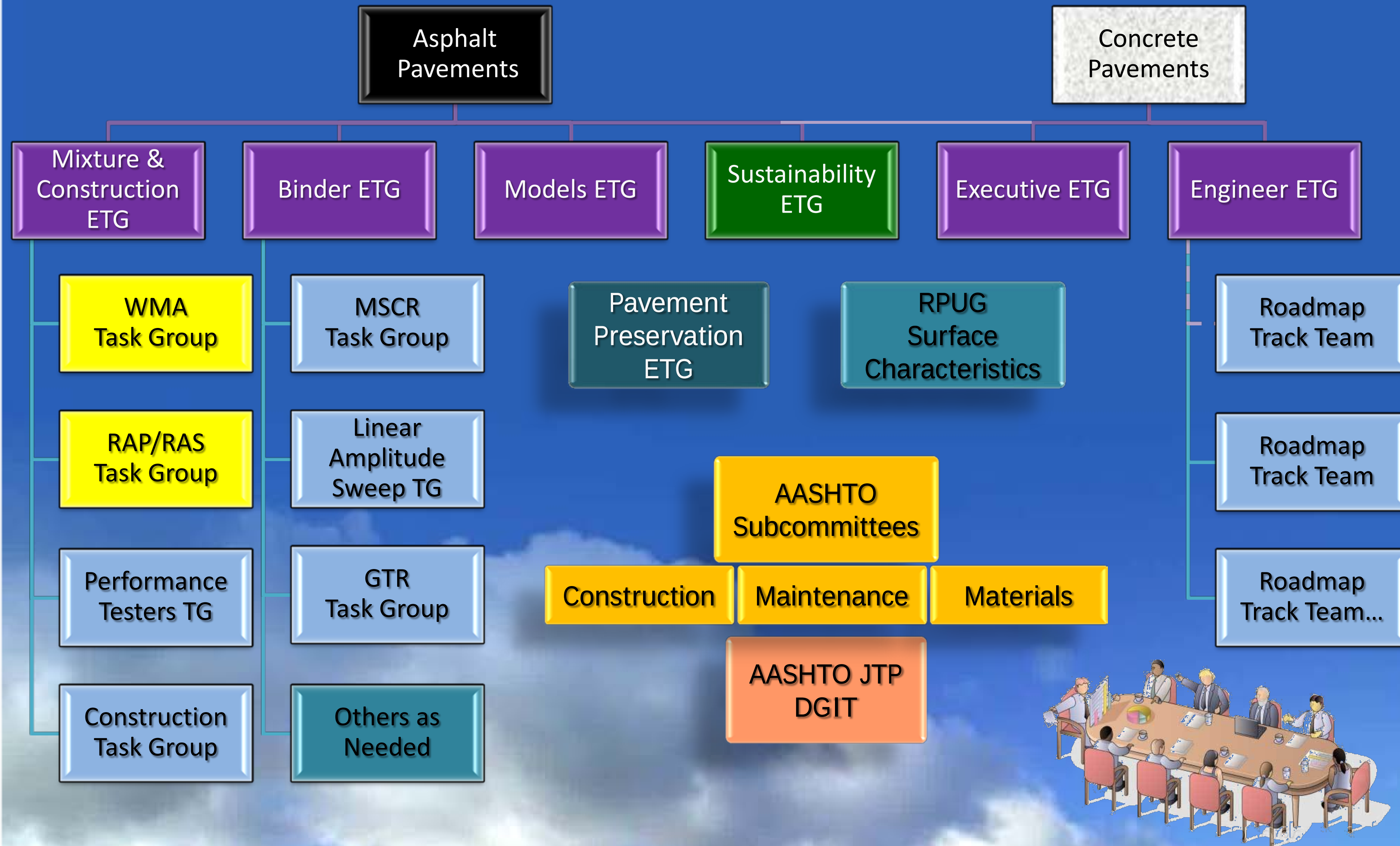
FHWA Pavement & Materials Program

Providing leadership and technology for the delivery of **long-life pavements** that meet our customers needs and are safe, cost effective, and can be effectively maintained.



U.S. Department of Transportation
Federal Highway Administration

Commitment to Stakeholder Engagement in the Pavement & Materials Program



" If you can't measure it, you can't manage it."

Peter Drucker

"A company's primary responsibility is to ***serve its customers****, to provide the goods or services which the company exists to produce. Profit is not the primary goal but rather an essential condition for the company's continued existence."*

Authorization

- MAP-21

  DIVISION A—FEDERAL-AID HIGHWAYS AND HIGHWAY SAFETY CONSTRUCTION PROGRAMS

  TITLE I—FEDERAL-AID HIGHWAYS

  Subtitle A—Authorizations and Programs

  - Asset Management Plan Requirements
  - Performance Management (Measures/Metrics)

What is…

1. Measure
2. Metric

A. Miles of
Good | Fair | Poor

B. IRI *(inches/mile)*

MAP-21

Performance Program

- Measures / Metrics
  - Pavements (Good|Fair|Poor)
    - IRI (Level 1)
    - *Structural*
    - *Functional*
    - *GOAL Composite*

Asset Management

(A) Listing of assets (condition)

(B) Objectives and measures

(C) Performance gaps

(D) LCC/Risk analysis

(E) Financial plan

(F) Investment strategies

Rulemaking Process

The Regulatory Process (Regulation, aka Rule)

…In simple terms, a FHWA document that may require the members of the public to do something, or prohibit them from doing something, is **a regulation**… FHWA authority to issue regulations comes from a number of different laws, and the FHWA issues regulations in a number of areas. However, to be valid, a regulation must not only be consistent with its underlying statute, but also **must be promulgated in a procedurally correct manner**…

Administrative Procedure Act (APA)

Pub.L. 79-404, 60 Stat. 237, enacted June 11, 1946

MAP-21 GOAL: 18 months

1
- Provides for public notice and opportunity for comment on proposed rules,

2
- Requires an agency to explain the basis and purpose for its rule, and

3
- Provides for judicial review of the agency's actions.

A Historical Perspective…
Customer Service

- There is no one perfect pavement, a pavement should meet the needs of the community and no more.

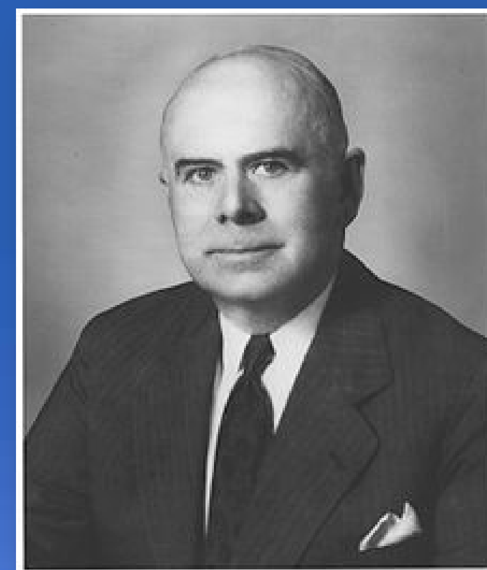
Community Needs *(Local to National)*

Safety *(Geometrics, Friction, SafetyEdge™…)*

Economics *(LCCA, Commerce, Growth)*

Ride *(Smoothness, Texture)*

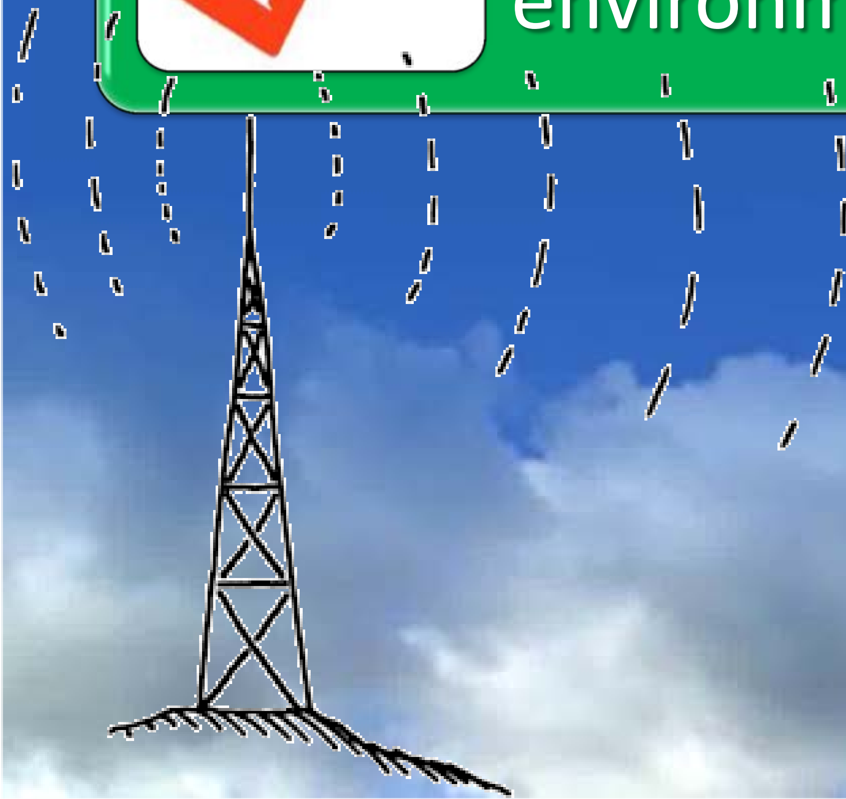
Environment *(Natural Resources, Recycled Products, Noise, Emissions…)*



Thomas "Chief" MacDonald
Iowa State Highway Commission
Early AASHO
Bureau of Public Roads c. 1919…

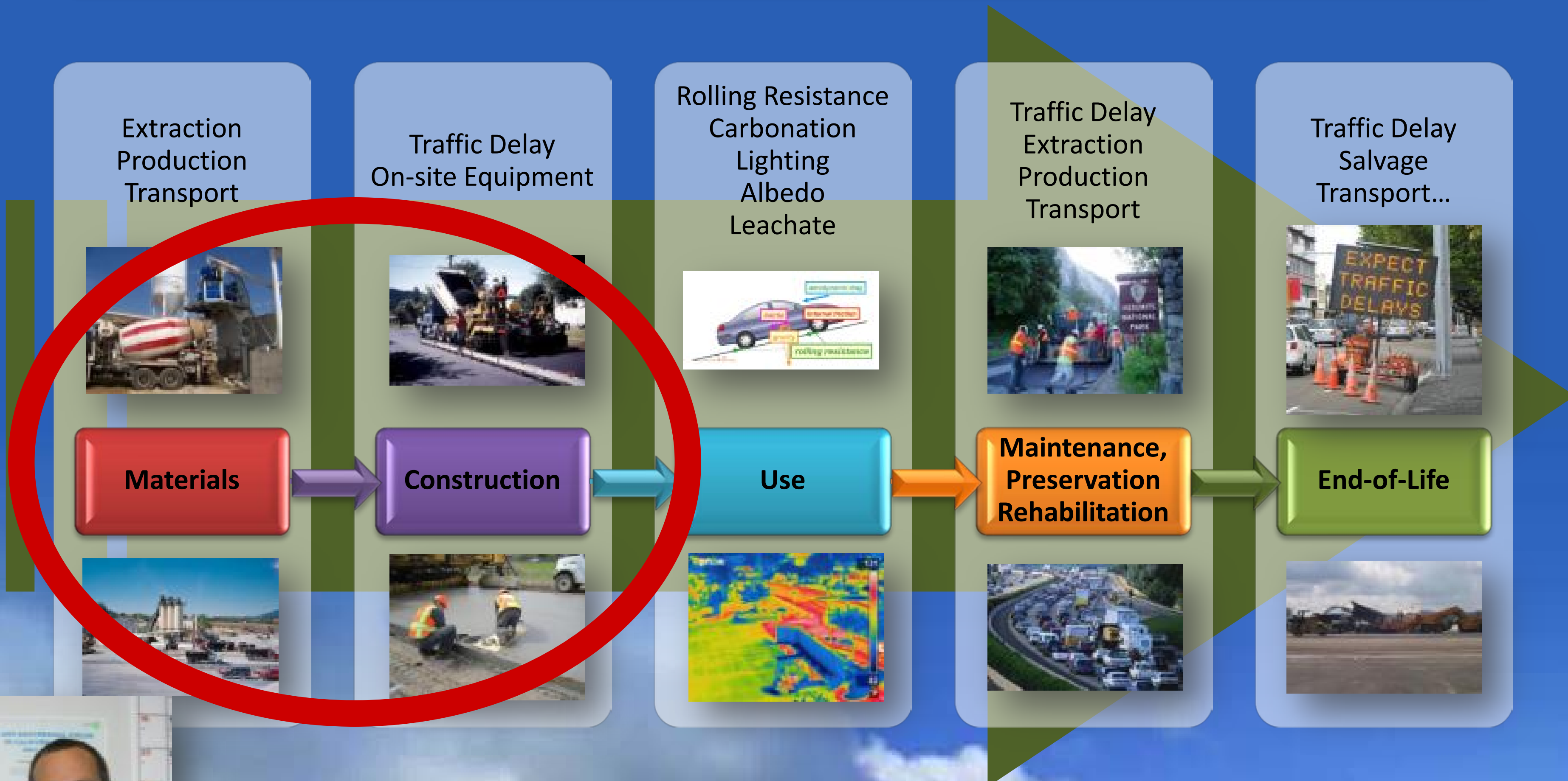
Key Pavement Question

Where are the greatest potentials, within our control, for reducing environmental impacts???



Pavement Life-Cycle

http://www.dot.ca.gov/newtech/roadway/pavement_lca/index.htm



CALIFORNIA DEPARTMENT OF
TRANSPORTATION

Ex. Estimate of Total US Emissions for <u>Hot-Mix Asphalt</u> Production

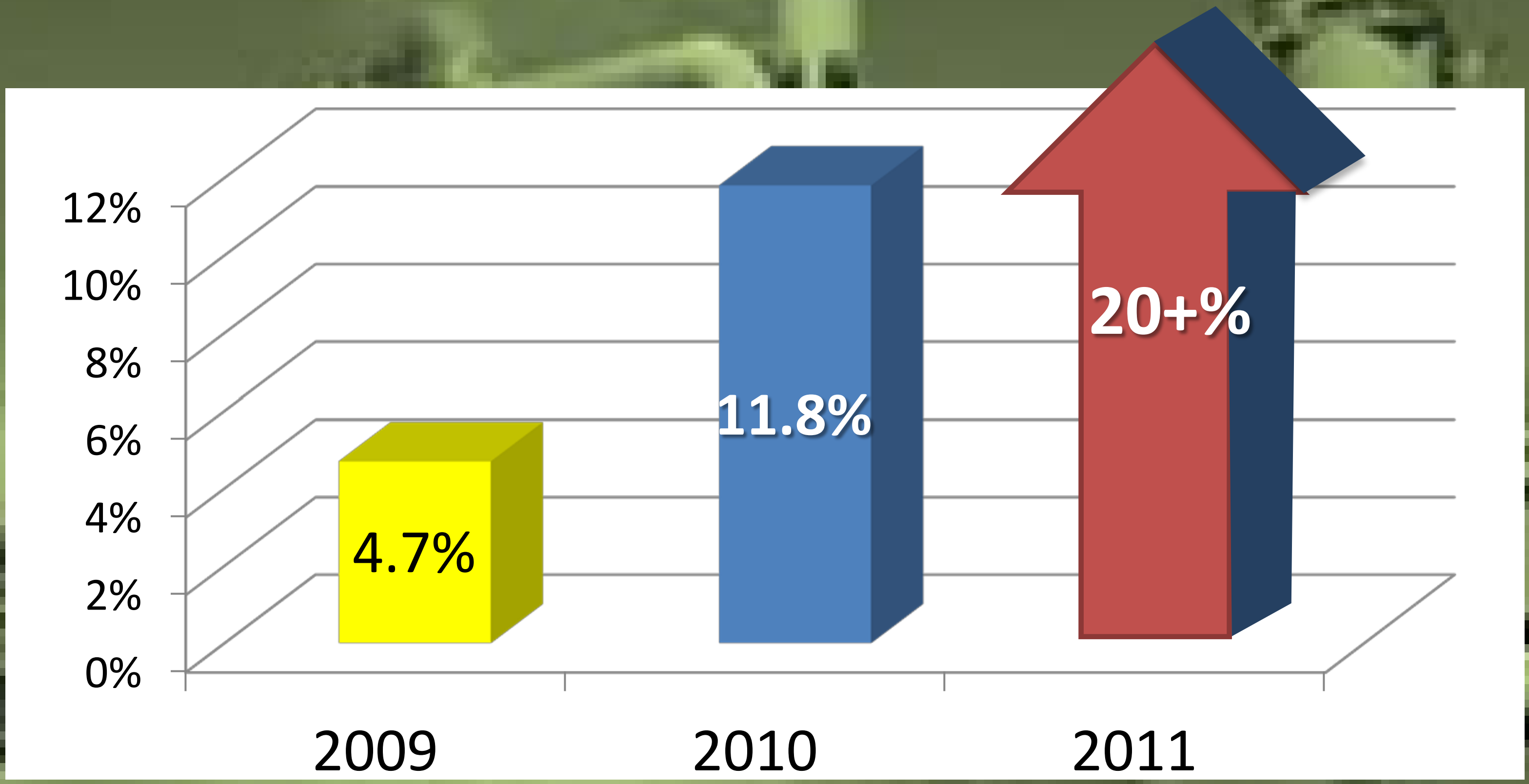
- Our Nation:
  - In 2011,
    380 million tons of asphalt mix
- Typical HMA Production Parameters
  - No. 2 Oil, 4% Stockpile Moisture
  - 330°F Mix Temperature (350°F Stack)
- Total Estimated Annual **<u>HMA</u>** Emissions ~
  - 8,222,000 US tons CO_2e

NATIONAL ASPHALT PAVEMENT ASSOCIATION

WMA Usage

Percentage of Total Asphalt Production in US

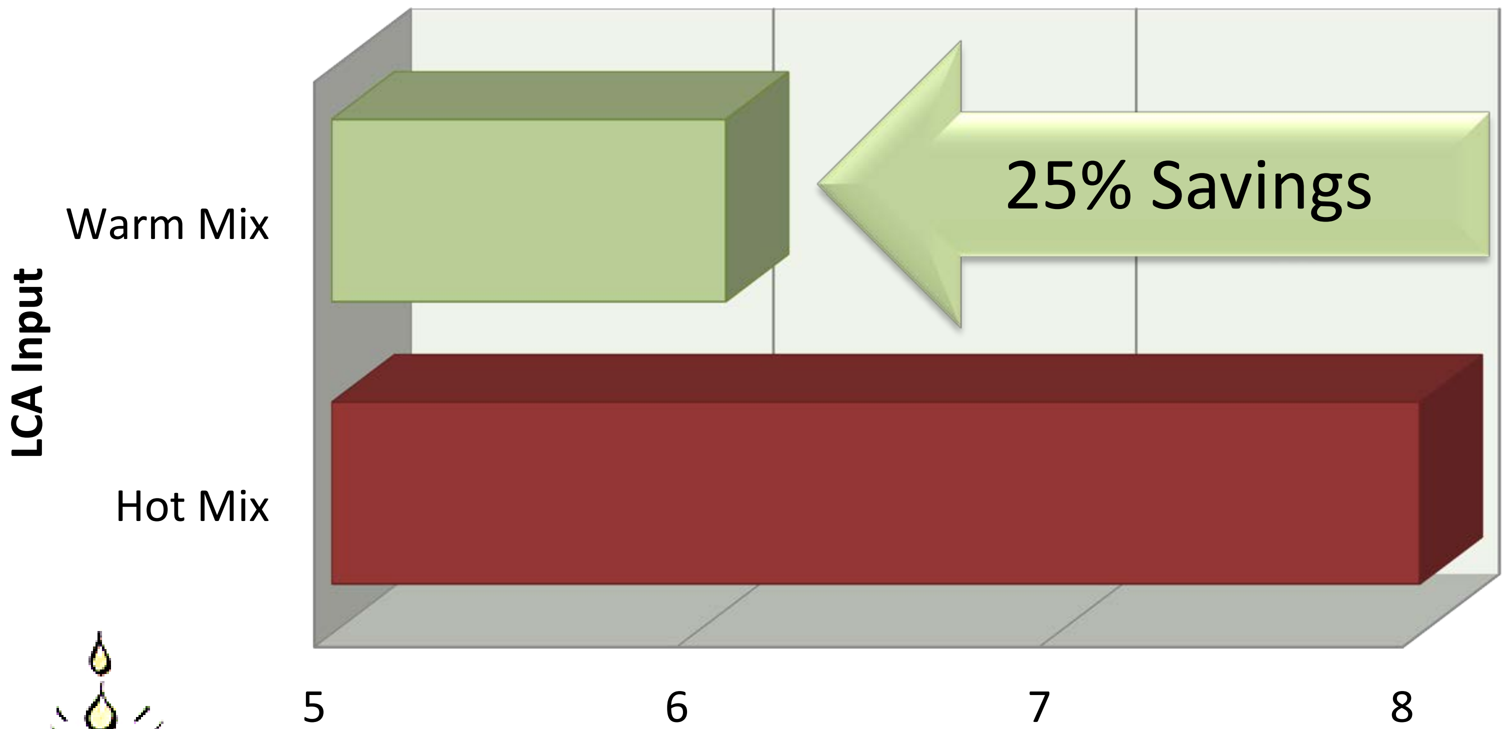
source: National Asphalt Pavement Association

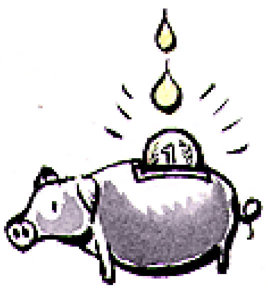


As the US continues to move from Hot-Mix to WMA

WARM-MIX ASPHALT

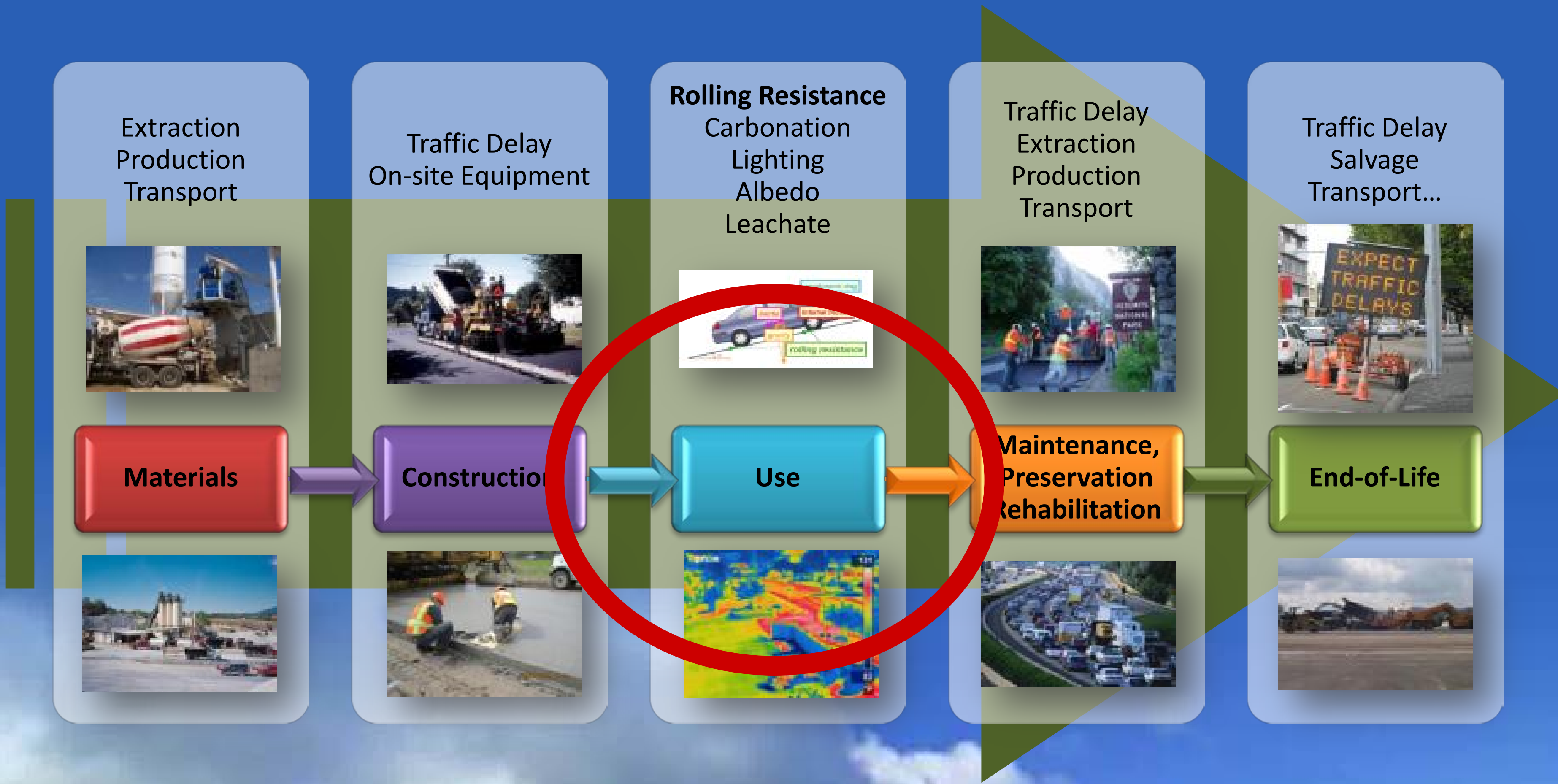
Equivalent of removing 1.5 million cars of the road each year!



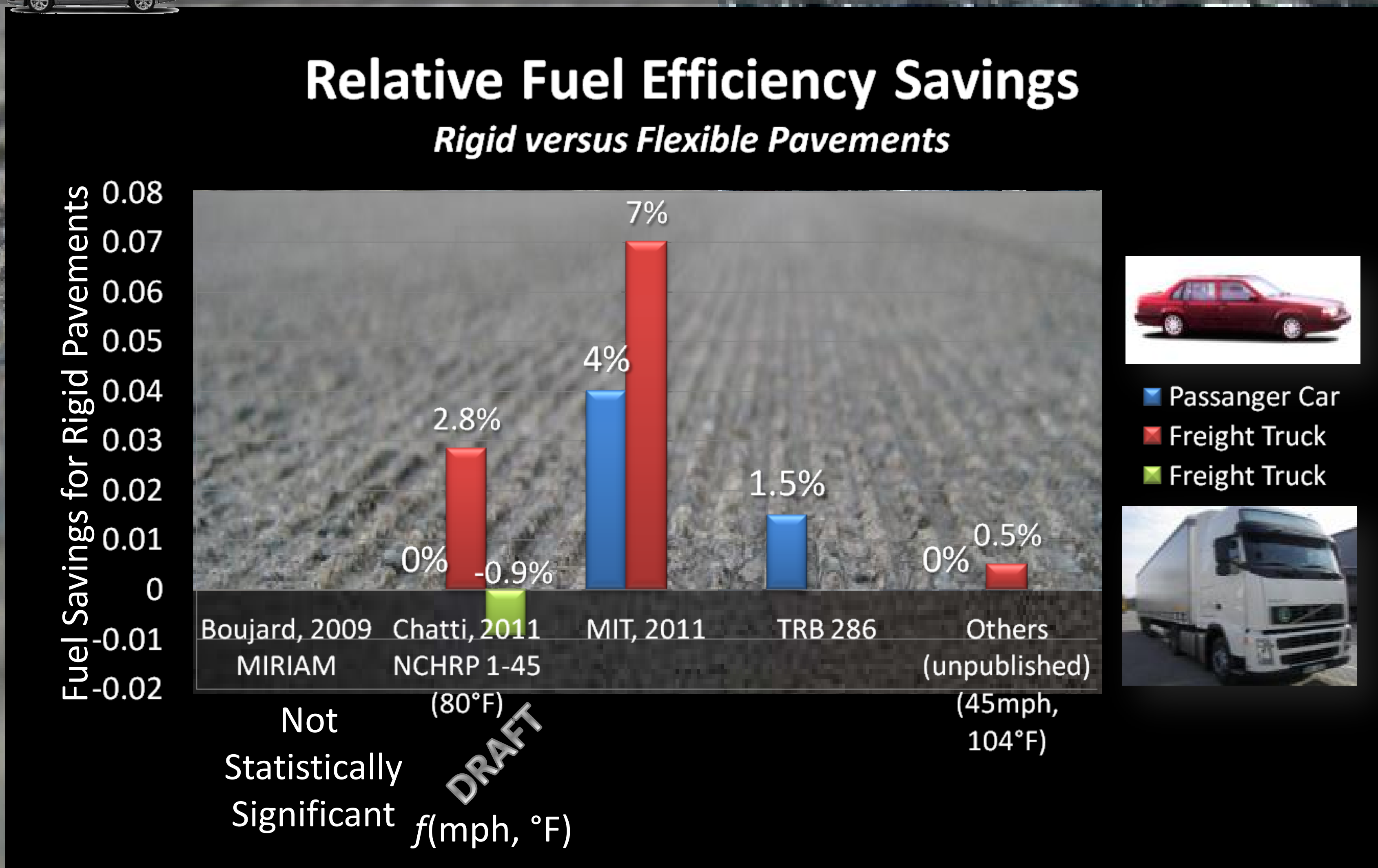


Total Predicted WMA Annual Emissions ~ 6,087,000 US tons CO_2e at 265°F

Recent Focus



Various Thoughts on Use Phase



How is this information being used?

Proving the Adage

For every Ph.D. there is an equal and opposite Ph.D.

Various Modeling Approaches

Texture + IRI + Speed = RR

MIRIAM

Deflection = RR

Massachusetts Institute of Technology

Texture + IRI + Grade, Super-elevation + Pavement Type + Speed Air Temp = VOC NCHRP 1-45

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

MIRIAM

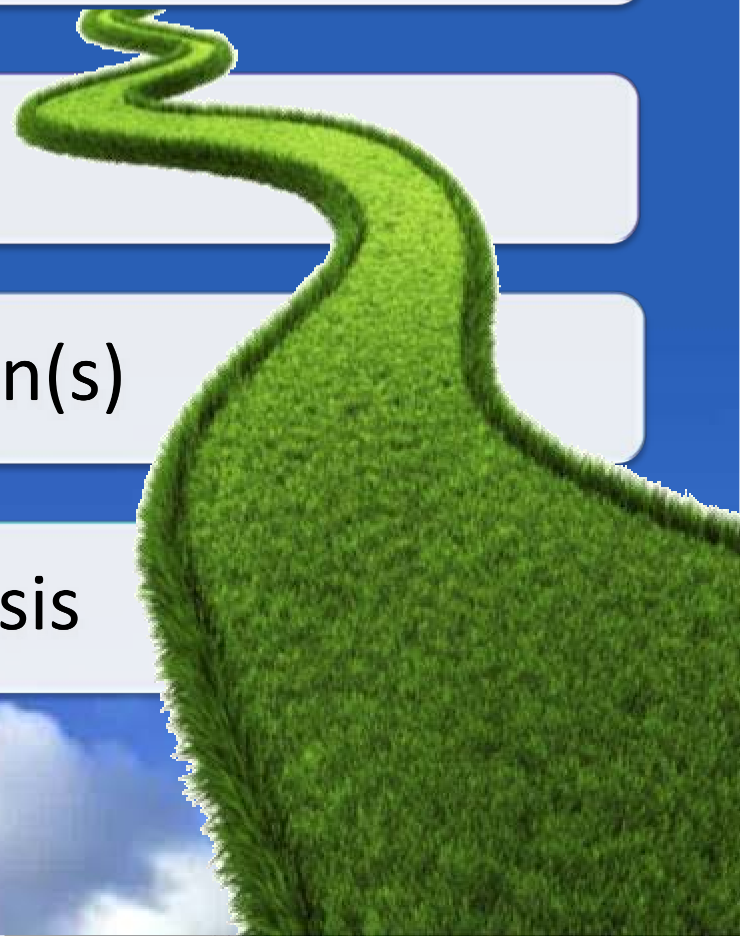
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Today's Visit

Understanding Use Phase

Vehicle Operation – Fuel Economy & Emissions

1. • Identify Relationships Needed for Analysis
2. • Identify Sources
3. • Define Pavement Section(s)
4. • Conduct Scenario Analysis



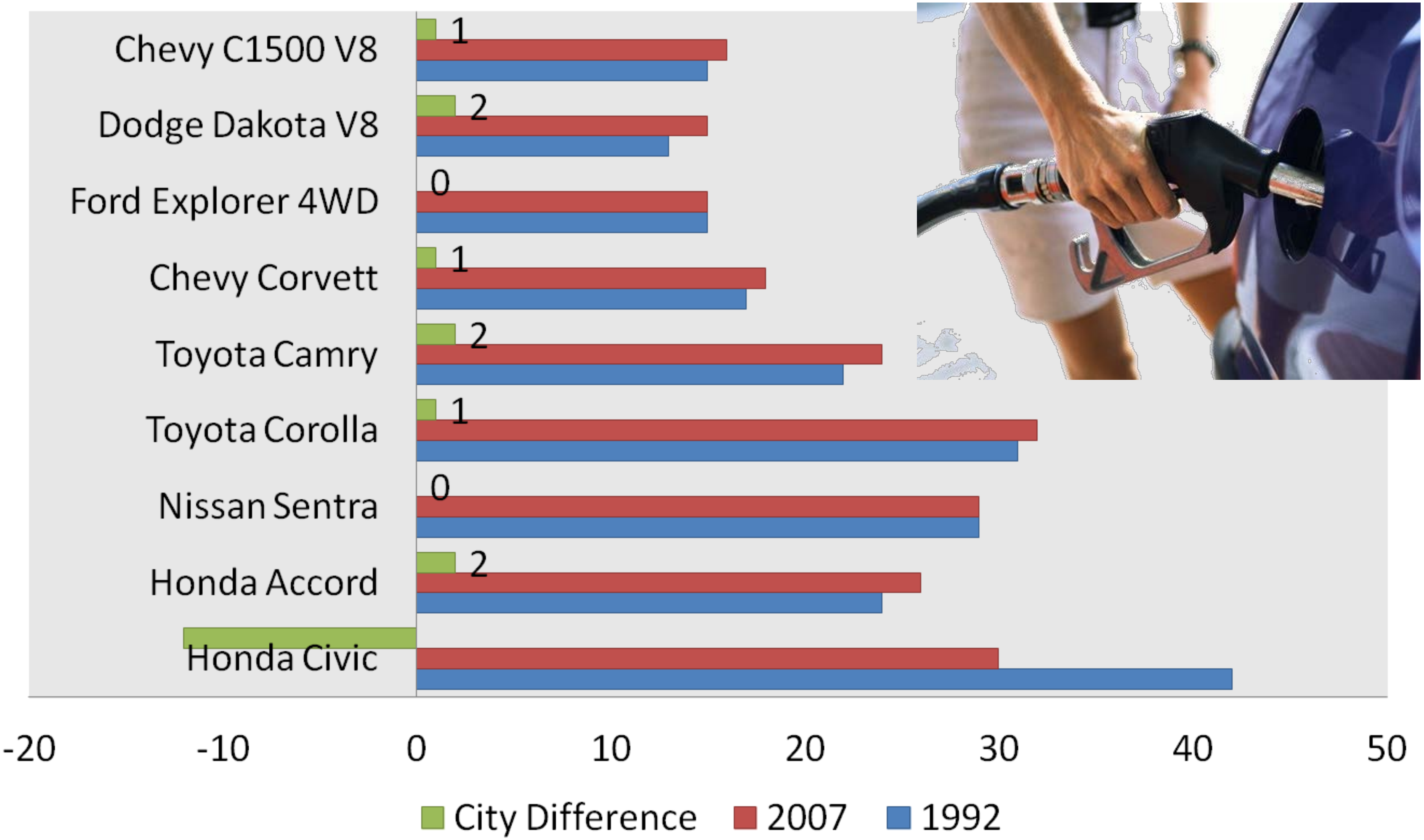
Fuel Efficiencies

- What is the US fleet-wide average for passenger cars (2011)?

A. **18.5 mpg**
B. **21.5 mpg**
C. **23.0 mpg**
D. **25.5 mpg**

Historic Changes in Fuel Economy

9 Models City MPG 1992 to 2007

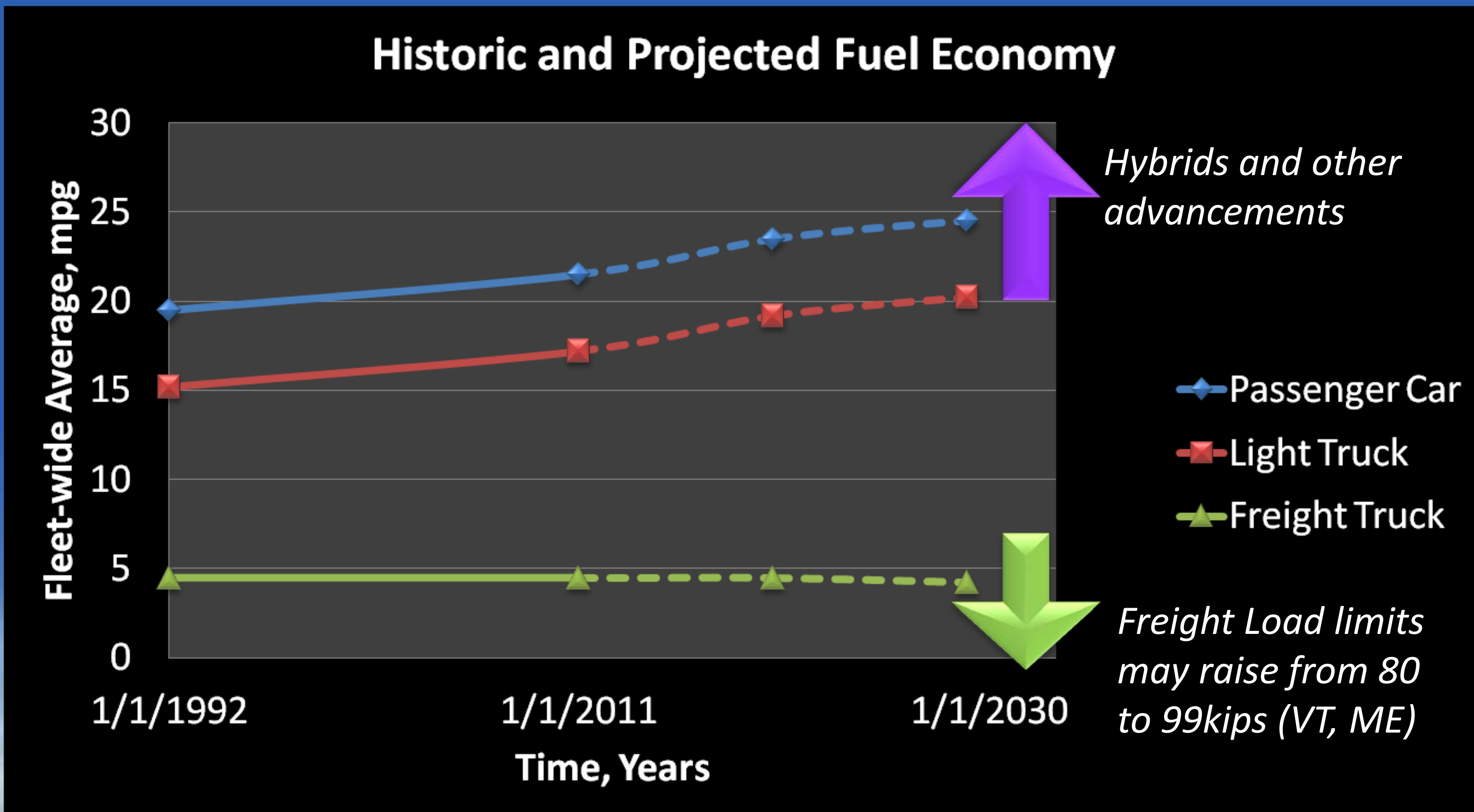


Fuel Efficiencies

- 18 Wheeler mpg diesel (carrying freight)
  - Low side ~ 4.5 mpg
  - High side ~ 11 mpg
  - Average ~ 7 mpg (used in analysis)

Reasonable to Assume

(But for Today: let's Assume NO Change)



What are the relationships between RR, fuel consumption, & Emissions?

Ongoing Effort

Road Directorate

MIRIAM: MODELS FOR ROLLING RESISTANCE IN ROAD INFRASTRUCTURE ASSET MANAGEMENT SYSTEMS

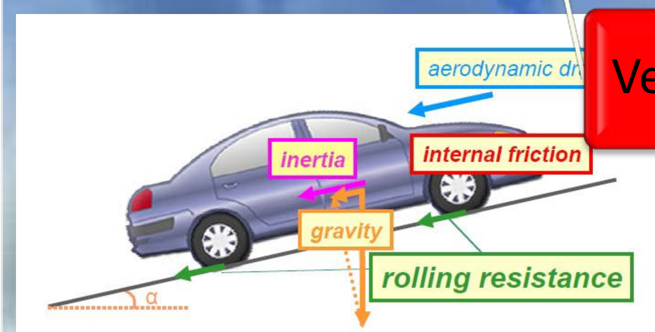
Bjarne Schmidt, Danish Road Directorate, Denmark

Factors Effecting Fuel Efficiencies
Total Driving **Resistance**

MIRIAM

- Vehicle Driving Resistance
  - Vehicle Propulsion
    - Inertial
    - Gravitational
    - Engine
    - Auxiliary Equipment
  - Vehicle Aerodynamics
    - Body Air
    - Tire Air
  - Vehicle Rolling
    - Tire/Road Rolling
    - Bearing
    - Transmission
    - Suspension

(Tire/Road Rolling, Bearing, Transmission, Suspension) } IRI/MPD



Rolling Resistance (RR)
Fuel Consumption & Emissions

- Present Knowledge
  - *Bjarne Schmidt, DRI, Denmark*

- Passenger Car at 60 mph
  - 50% of fuel consumption to overcome RR
- Truck at 50 mph
  - 40% of fuel consumption to overcome RR
- On Average

  ~25% of fuel consumption is used to overcome RR

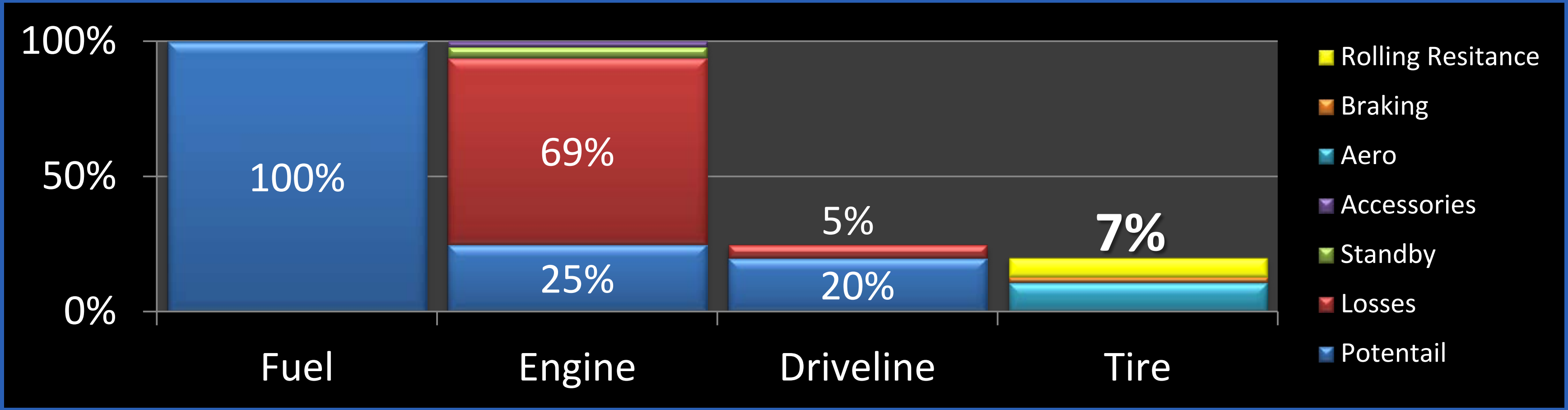
MIRIAM

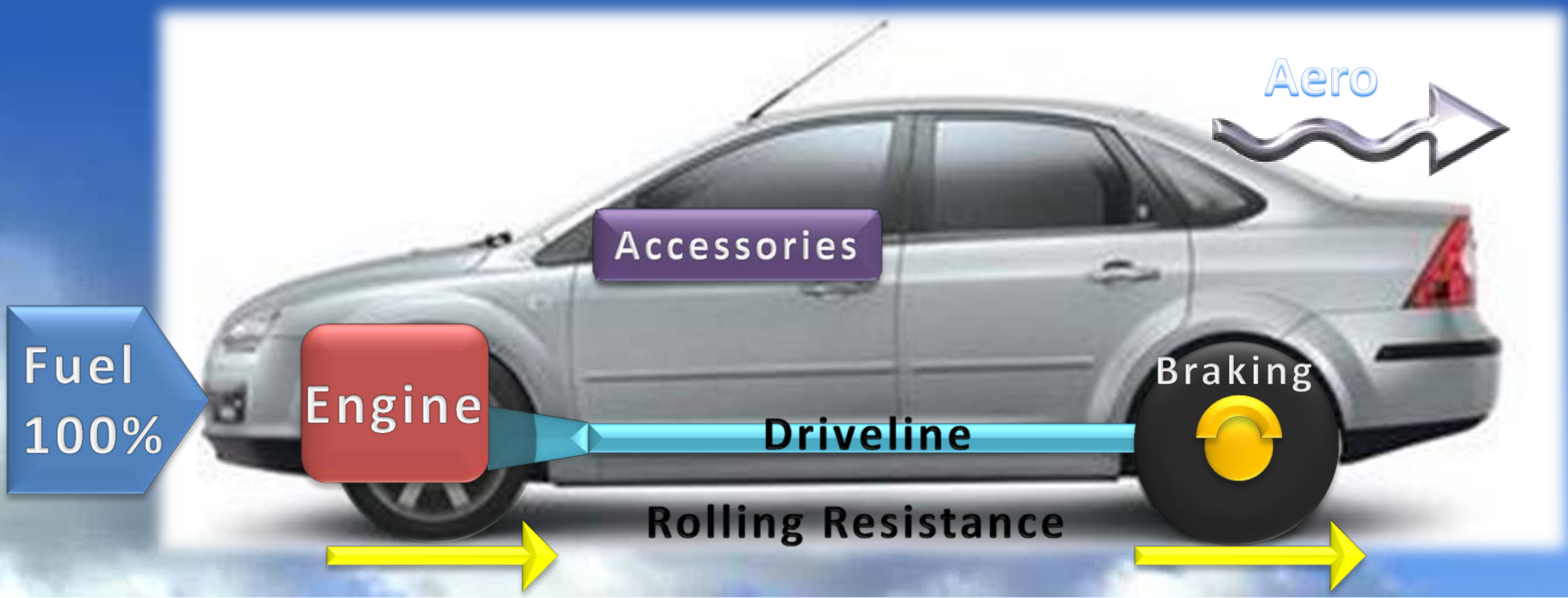
Tire Wear, Traction, & Force Generation
Automotive View on Rolling Resistance

- Operation of a mid-sized gasoline fueled car like a Chevrolet Malibu or Ford Focus.

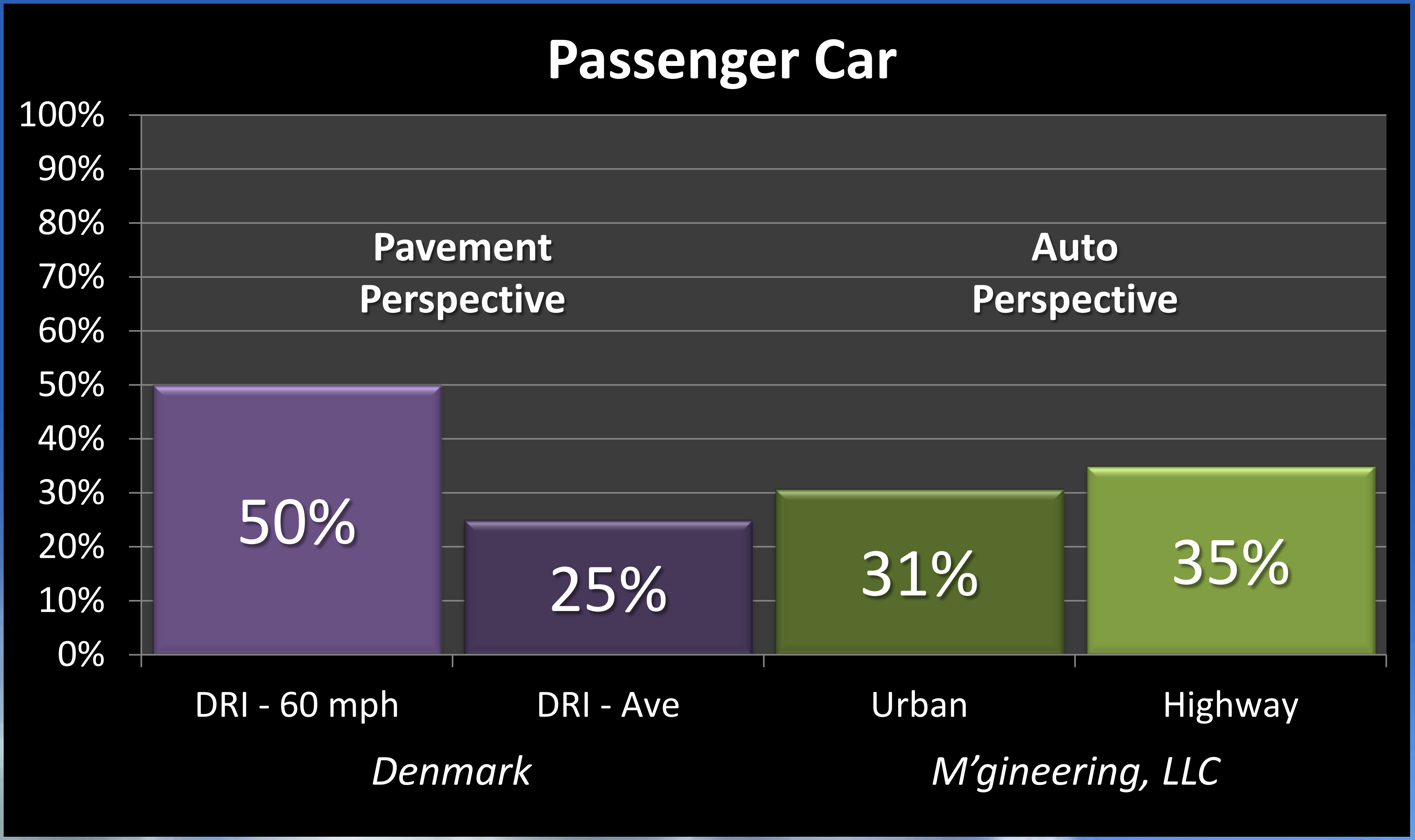
Alternatively: Highway Driving

(Source: M'gineering, LLC: Dr. Mariom Pottinger)





Fuel Consumptions to Overcome RR
RR Loss / Driveline Potential




So Abbot, rolling resistance accounts for about a third of fuel consumption? But who's on first?

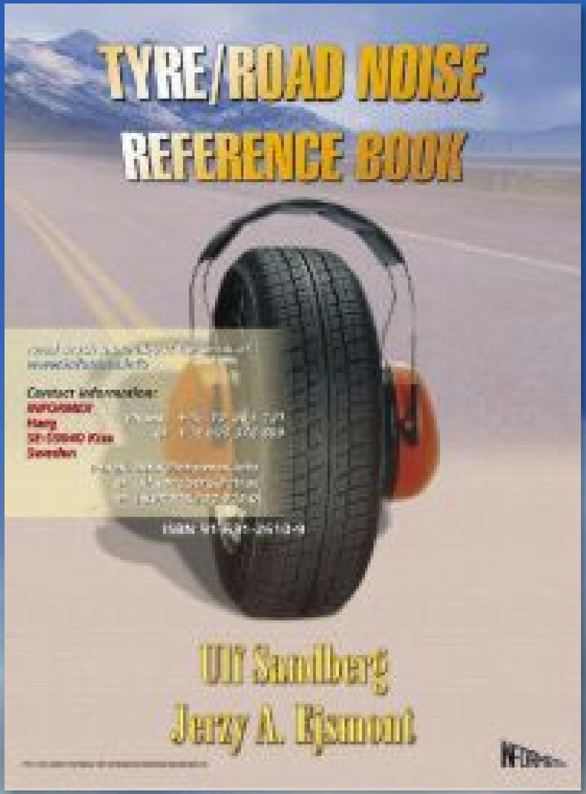
From a Pavement Perspective
What is in Our Control?

- Yes — Texture, *f*(time)
- Yes — Stiffness, *f*(design)
- No — Temperature, *f*(nature)
- Yes — Smoothness, *f*(time)

Texture

Understanding Tire/Pavement Interaction

- Key Reference:
  - Tyre/Road Noise Reference Book

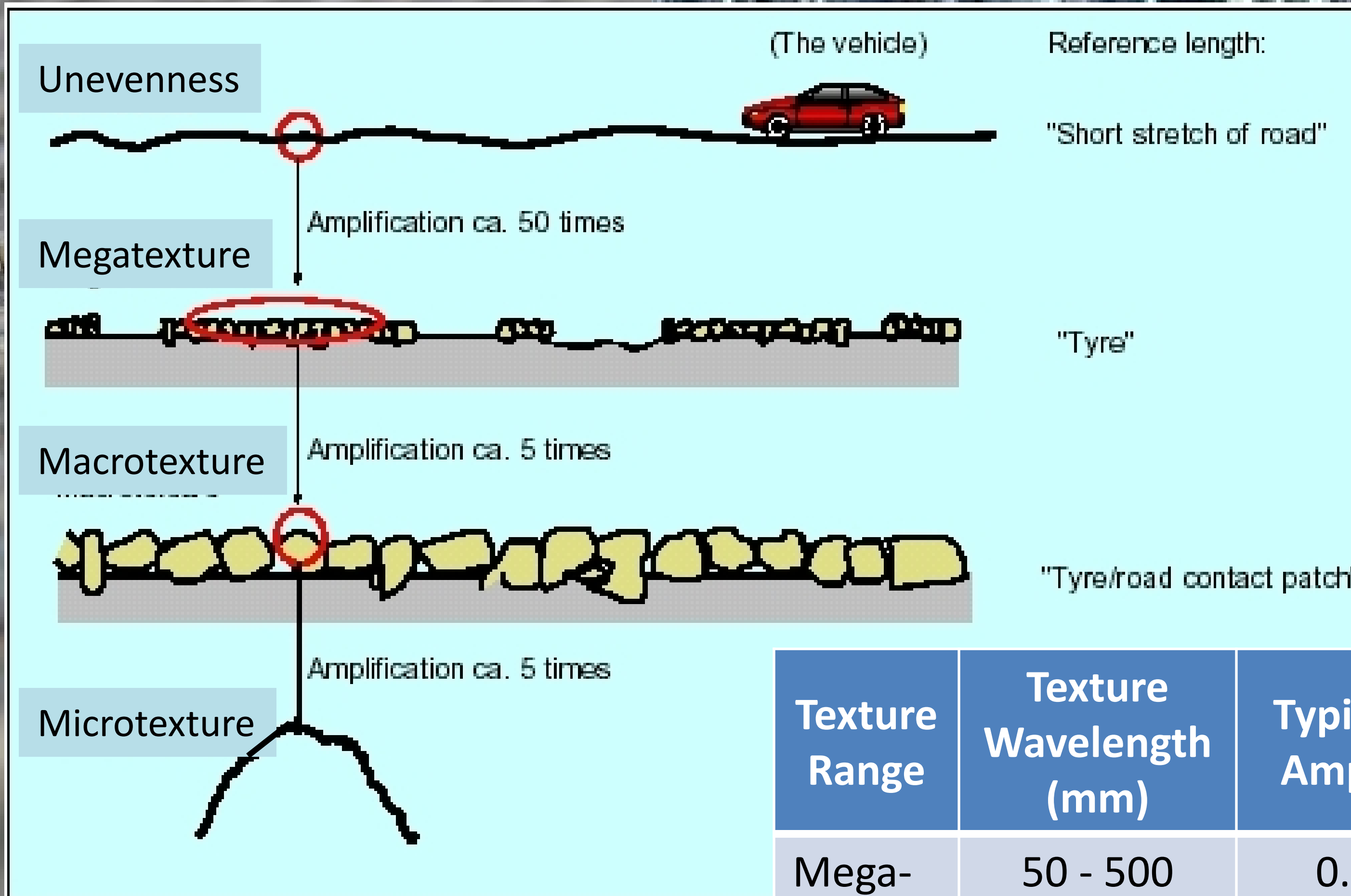


Ulf Sandberg

Jerzy A. Ejsmont

Pavement Texture Ranges

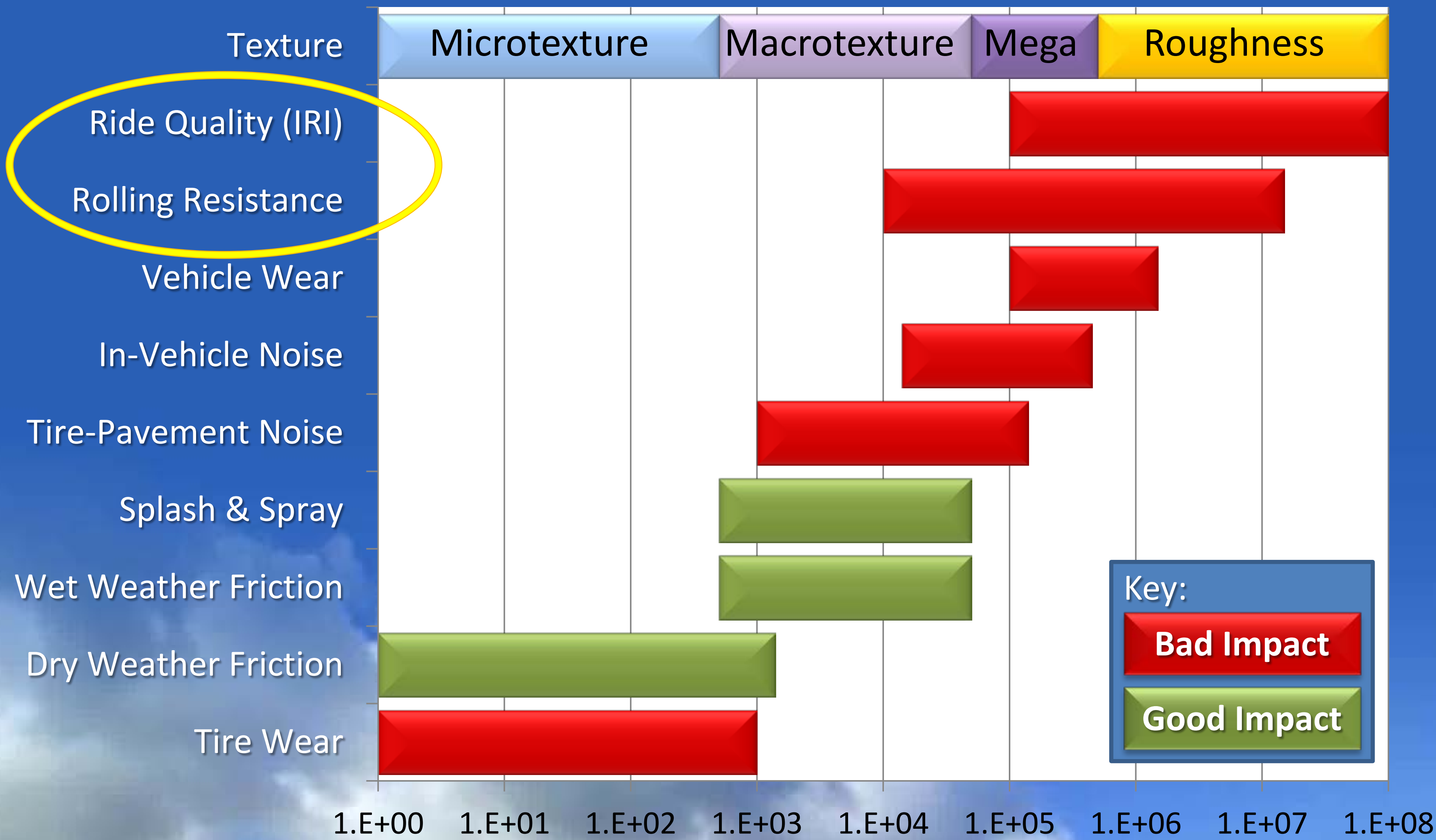
Defined by Sandberg, et.al.



Texture Range	Texture Wavelength (mm)	Typical Peak Amplitudes
Mega-	50 - 500	0.1 – 50
Macro-	0.5 – 50	0.1 – 20
Micro-	< 0.5	0.001-0.5

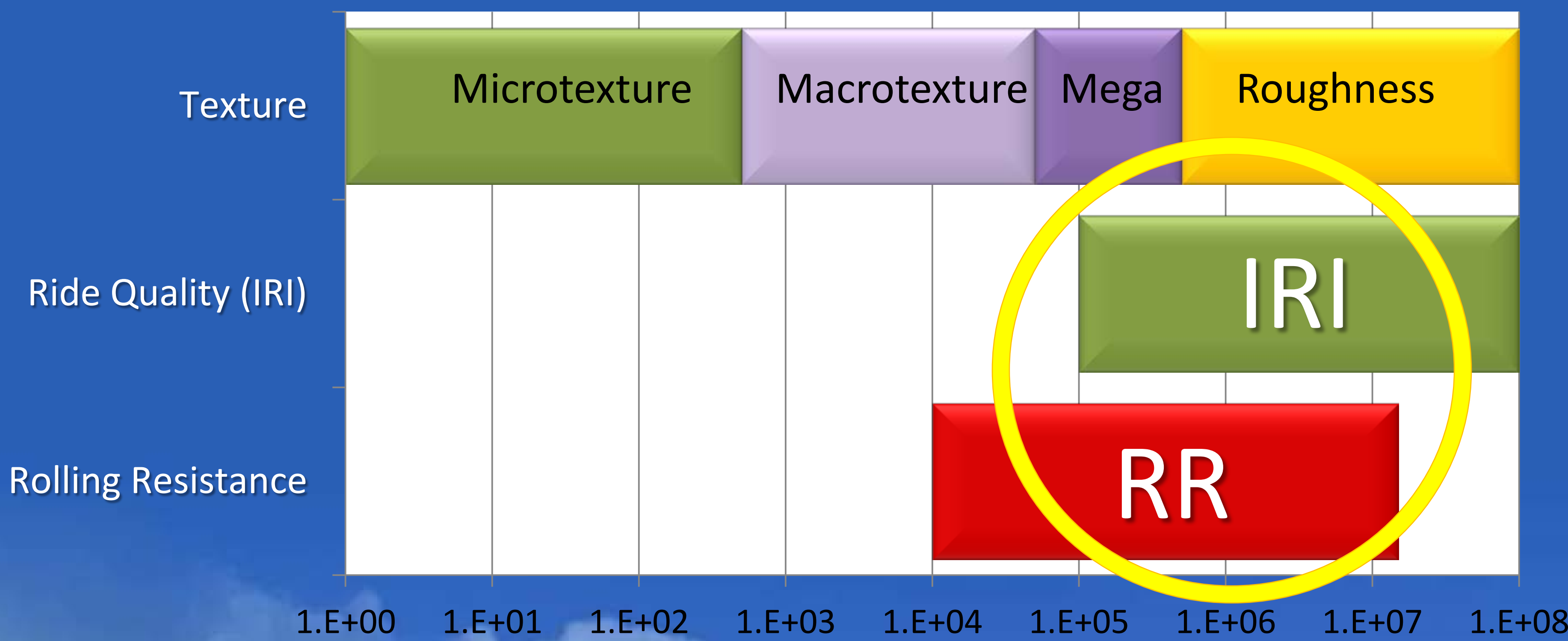
PIARC Pavement Surface Characterizes

(Scale: µm, 10^{-6} m)



Dependent on Similar Textural Range

(Scale: µm, 10^{-6} m)



Key:

- **Bad Impact**
- **Good Impact**

- **Measure = Texture (Macro, Mega, Roughness)**
- **Measure = Ride Quality**
- **Outcome = Rolling Resistance = *f*(IRI, Texture…)**

Texture

As Relates to Rolling Resistance

When did Engineers first start exploring concepts of rolling resistance on pavements?

A. Mid 1800's (Horse-drawn carriages)
B. Early 1900's (Trail Road Associations)
C. Mid 1900's (Bureau of Public Roads)
D. Late 1900's (pending '97 Kyoto Protocol)
E. I like Ice cream

A Little History… 1845

Robert W. Thompson, a Scottish engineer, received a British patent for his new pneumatic carriage tire greatly reducing rolling resistance force.

Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1233.] SATURDAY, MARCH 27. [Price 3d.

Edited by J. C. Robertson, 166, Fleet-street.

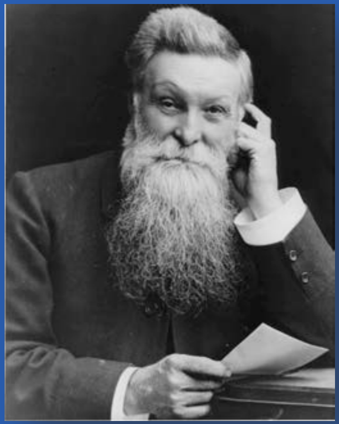
THOMSON'S PATENT AERIAL WHEELS.

Fig. 1.

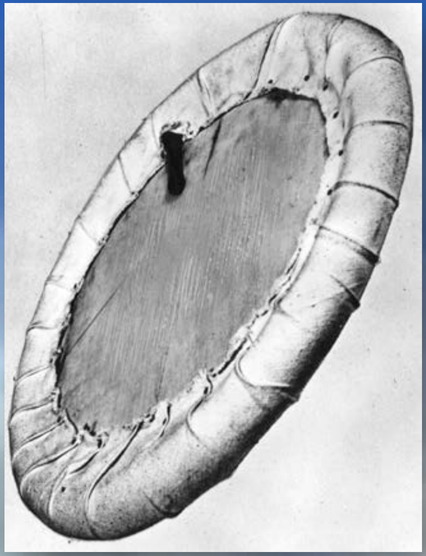
Result of Experiments tried by Messrs. Whitehurst and Co., and the Patentee, for ascertaining the comparative Draught of R. W. Thomson's Patent Aerial Wheels and the common Wheels. Tried in Regent's Park, March 17, 1847.

Weight of Carriage, $10\frac{1}{2}$ cwts.	Common Wheels. Actual draught in pounds.	Patent Wheels. Actual draught in pounds.	Saving of draught by Patent Wheels,
Over a smooth, hard, macadamized level road	45	28	60 per cent.
Over new broken flints................	120	$38\frac{1}{2}$	310 per cent.

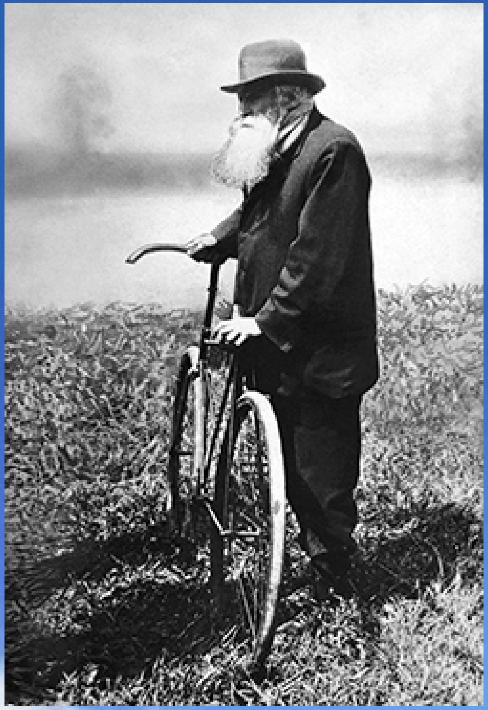
1888 ~ 40 Years Later…



John Boyd Dunlop, who knew nothing of Thompson, invented the pneumatic tire to improve the horrible ride of the now common bicycle



Right tire – right time
Business boomed!

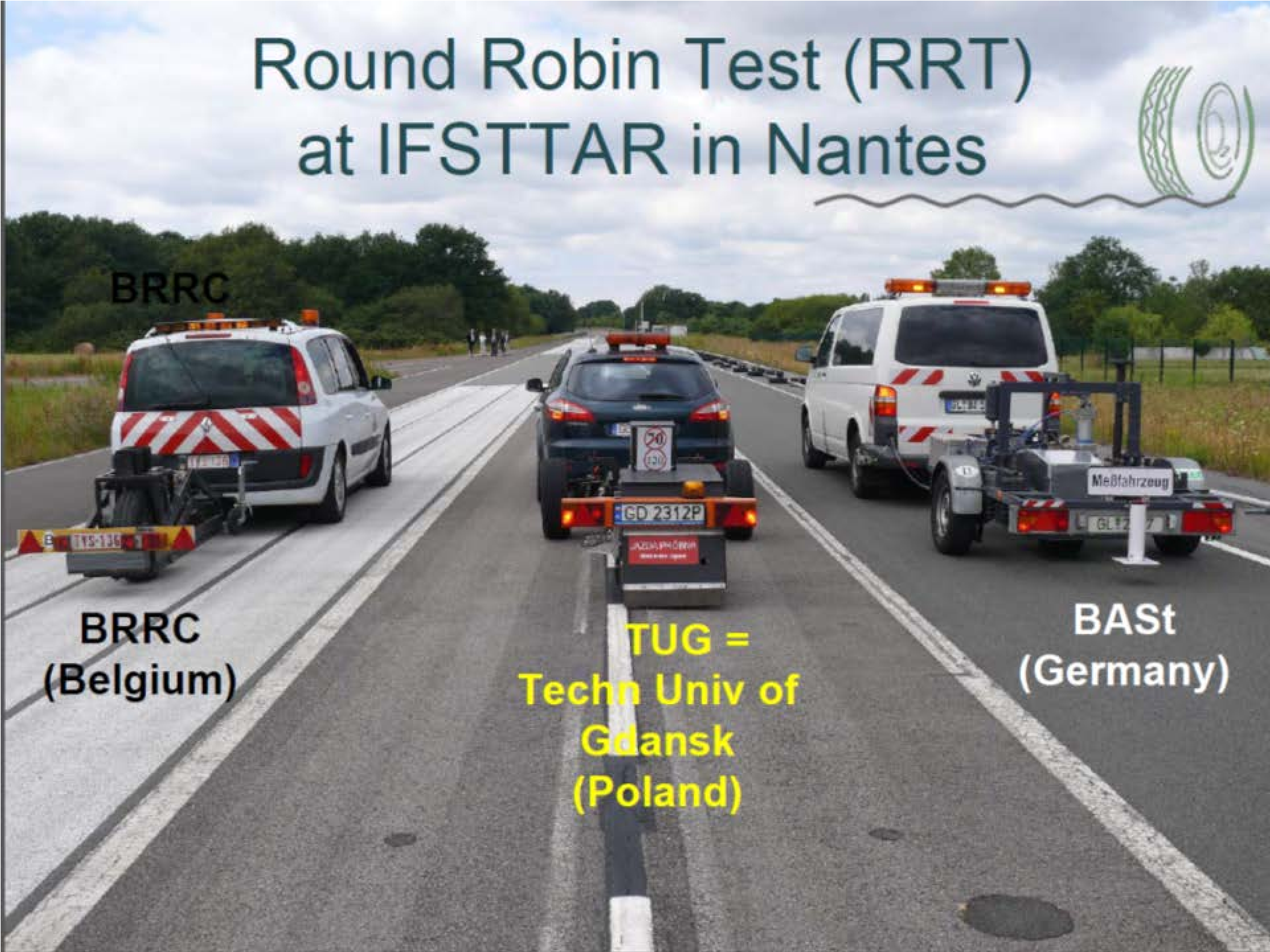


1888 Dunlop Rolling Resistance Test

Dunlop just rolled his tire across the courtyard. His would go far enough to hit the wall. The solid tire would not. (AASHTO TP 001) ☺

Fast Forward 165 years

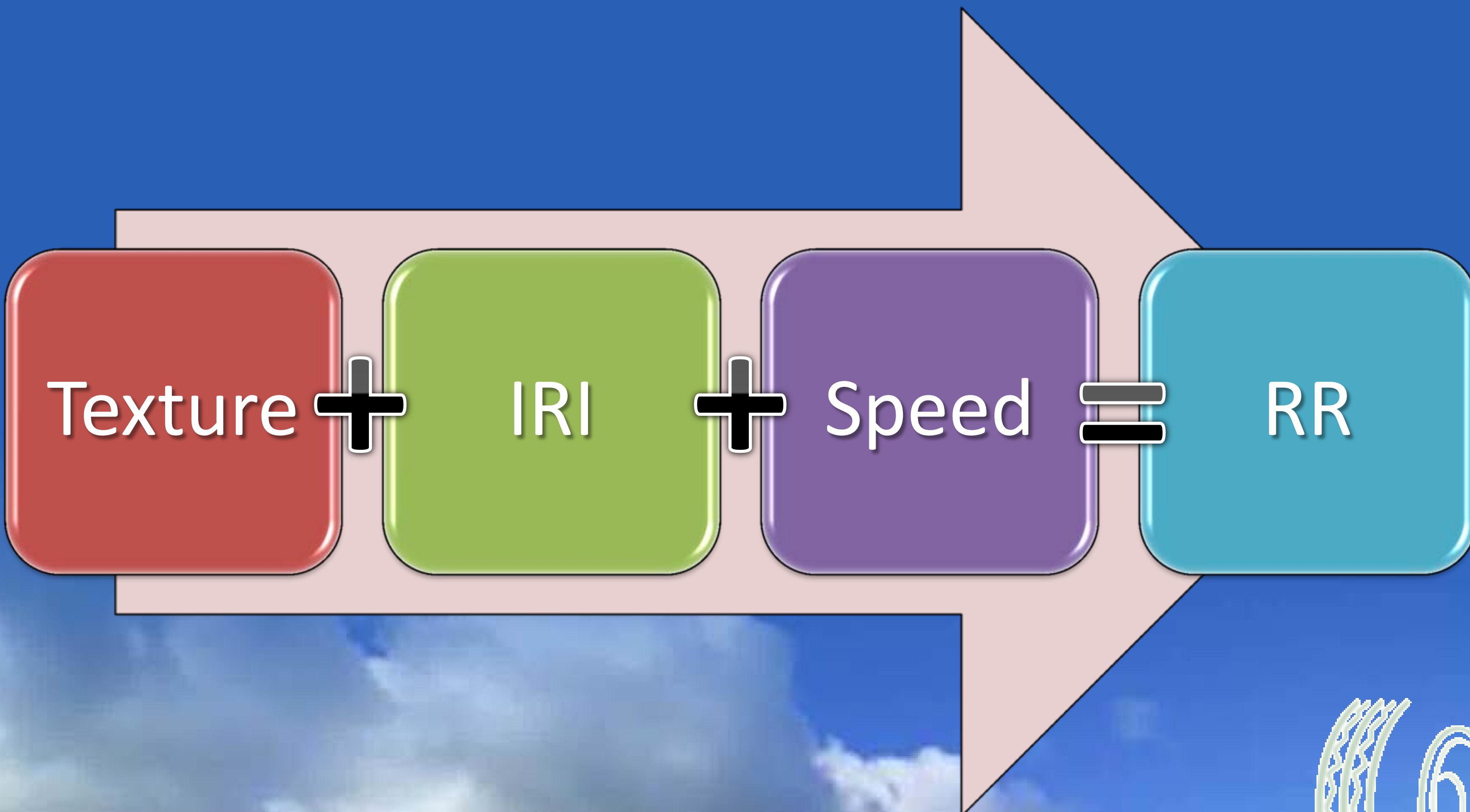
- Rolling Resistance
  - Direct Measurement
  - Modeling RR from Pavement Surface Characteristics


Round Robin Test (RRT)
at IFSTTAR in Nantes
BRRC
BRRC
(Belgium)
TUG =
Techn Univ of
Gdansk
(Poland)
BASt
(Germany)
GD 2312P
Meßfahrzeug

US RR Device?

- Most research in the US has focused on tire and vehicle drag…
- Automotive perspective.

MIRIAM Modeling Rolling Resistance



MIRIAM

$RRC = C_1 + C_2\,MPD + C_3\,IRI + C_4\,IRI\,(V - V_{ref})$

For a car:

$$RRC = 0.0148 + 0.0020 \cdot MPD + 0.00064 \cdot IRI + 0.00005 \cdot IRI \cdot (V - 20)$$

Volvo 940 2-tires

For a truck:

$$RRC = 0.0061 + 0.0014 \cdot MPD + 0.00095 \cdot IRI + 0.000076 \cdot IRI \cdot (V - 20)$$

Volvo FH-480, 27tons

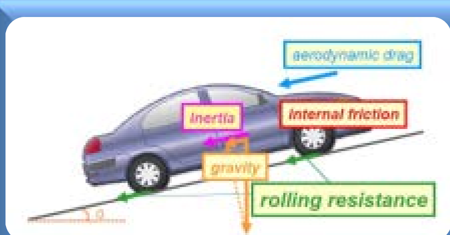
Where:

- MPD: Mean Profile Depth (macrotexture) in mm
- IRI: International Roughness Index in mm/m
- V: Vehicle Speed in meter/second

MIRIAM

What is the potential impact of RR on fuel efficiency?
EU – Energy Conservation in Road Pavement Design

10 % ↑ RR ~ 3% ↑ Fuel Consumption

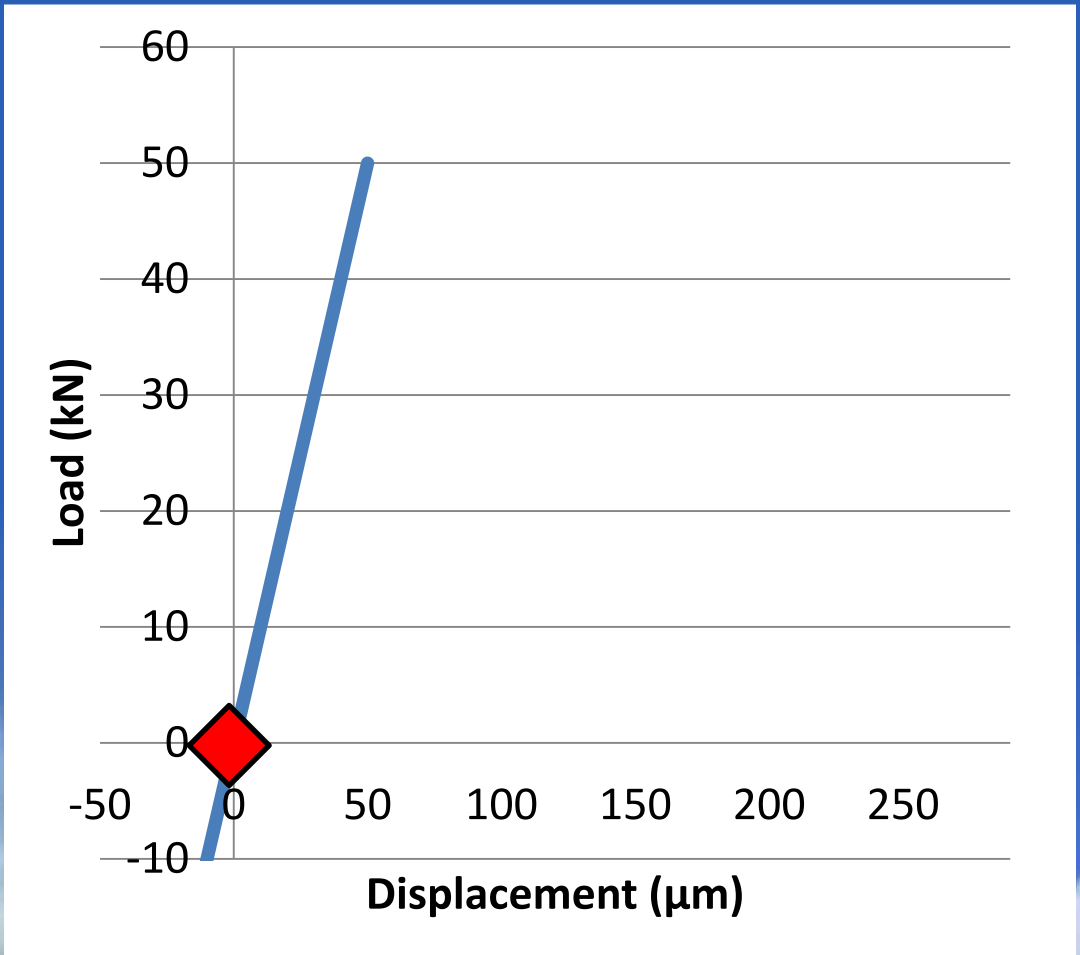


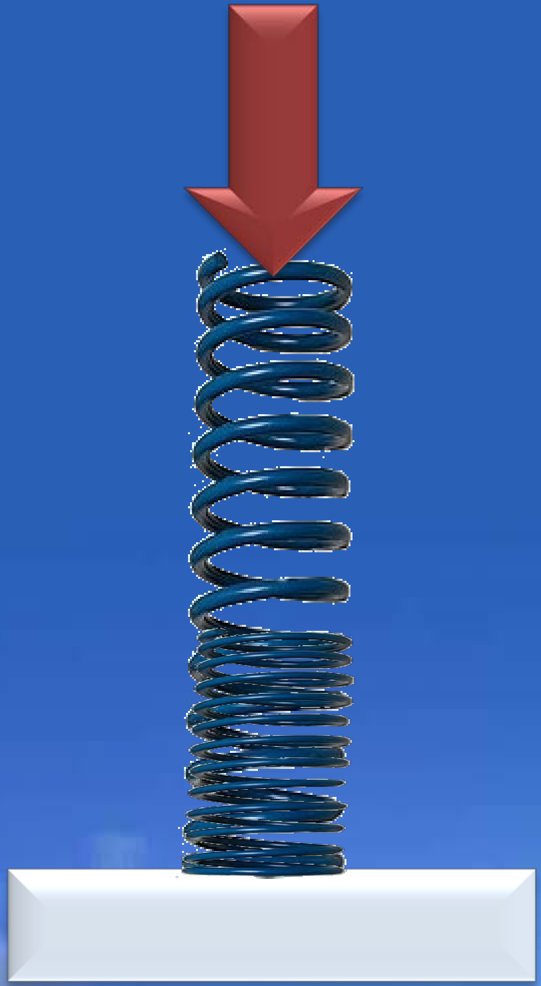
10:3

Road Directorate

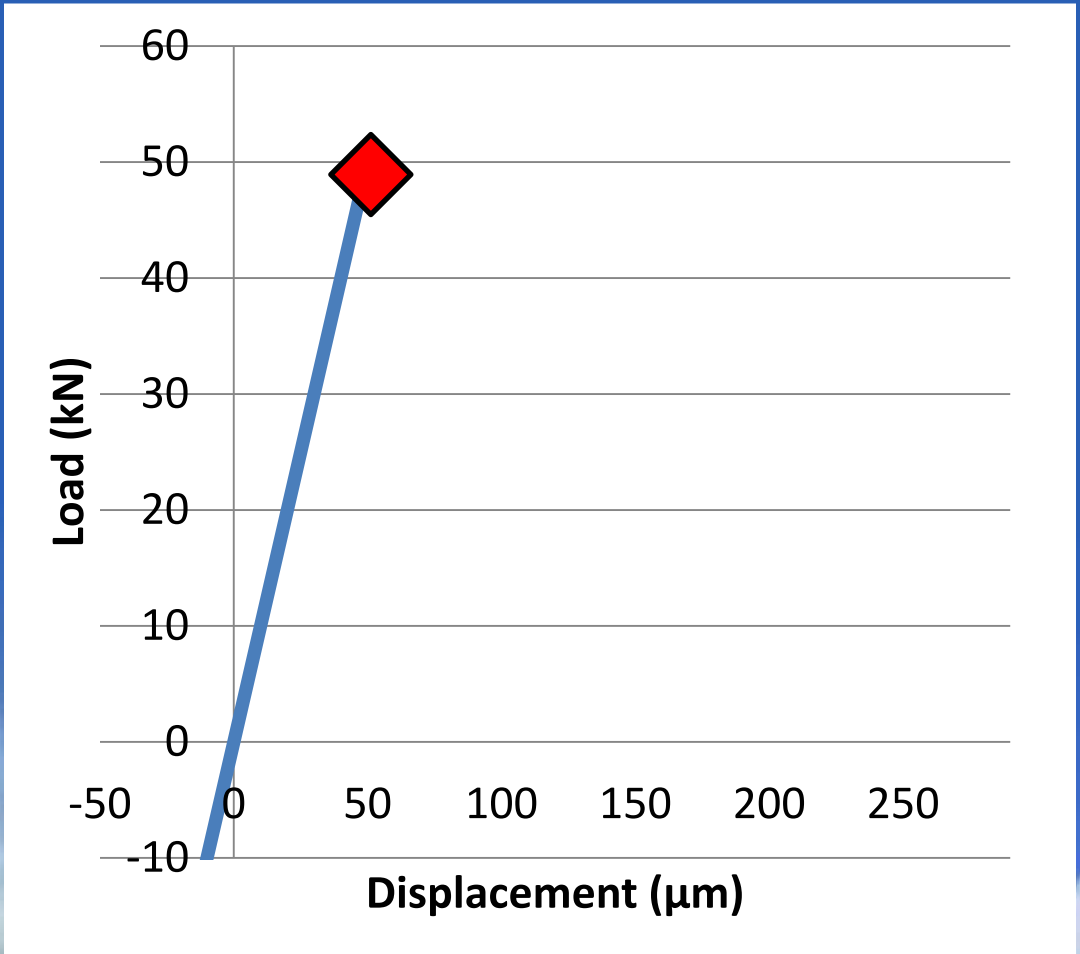
Stiffness

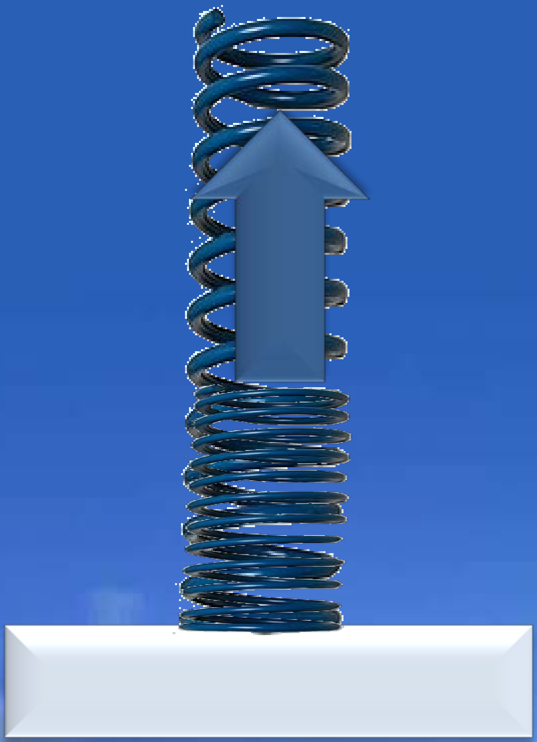
Stiffness Concept
Ideal Spring: load/unload *(no losses)*



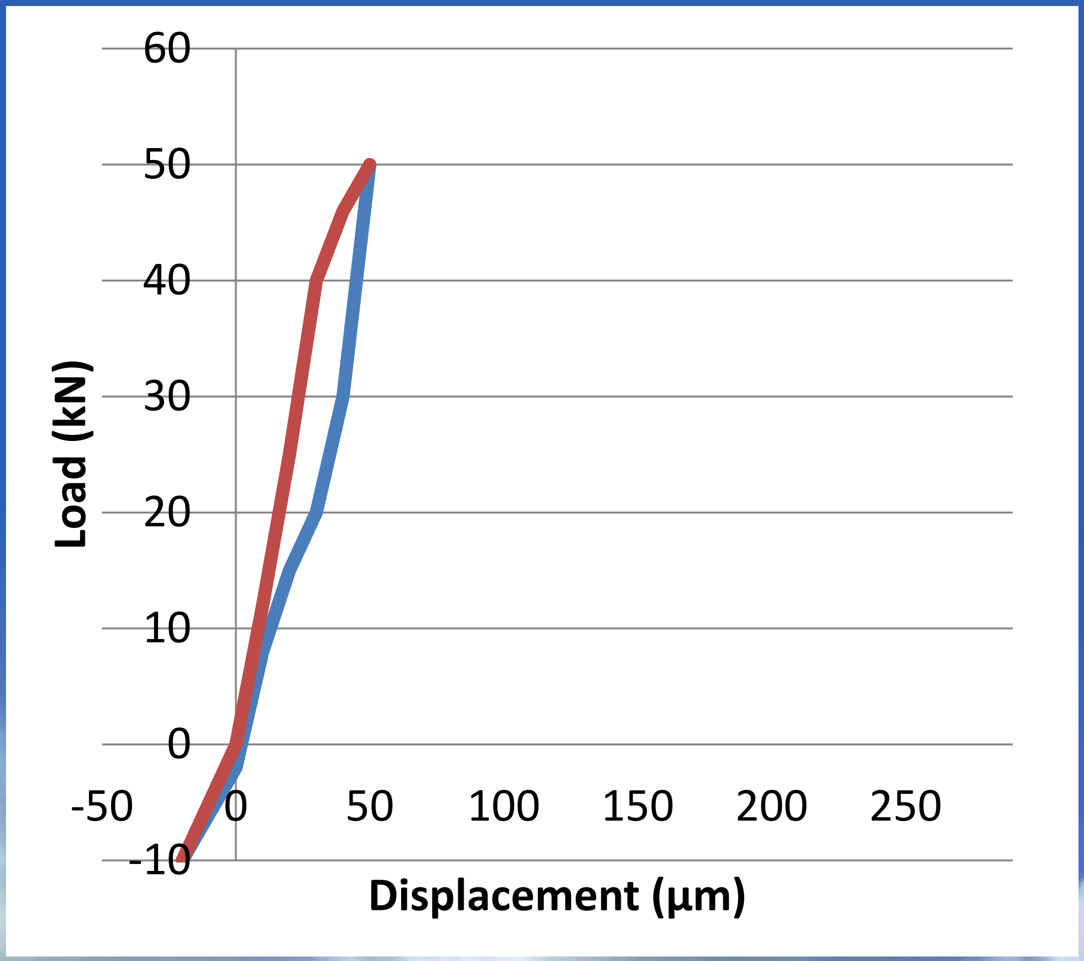


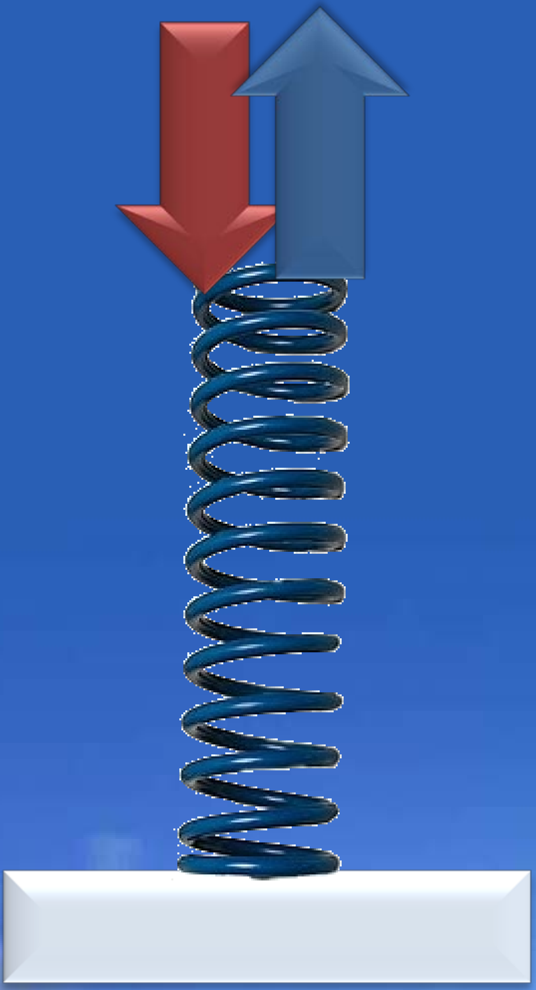
Stiffness Concept
Ideal Spring: load/unload



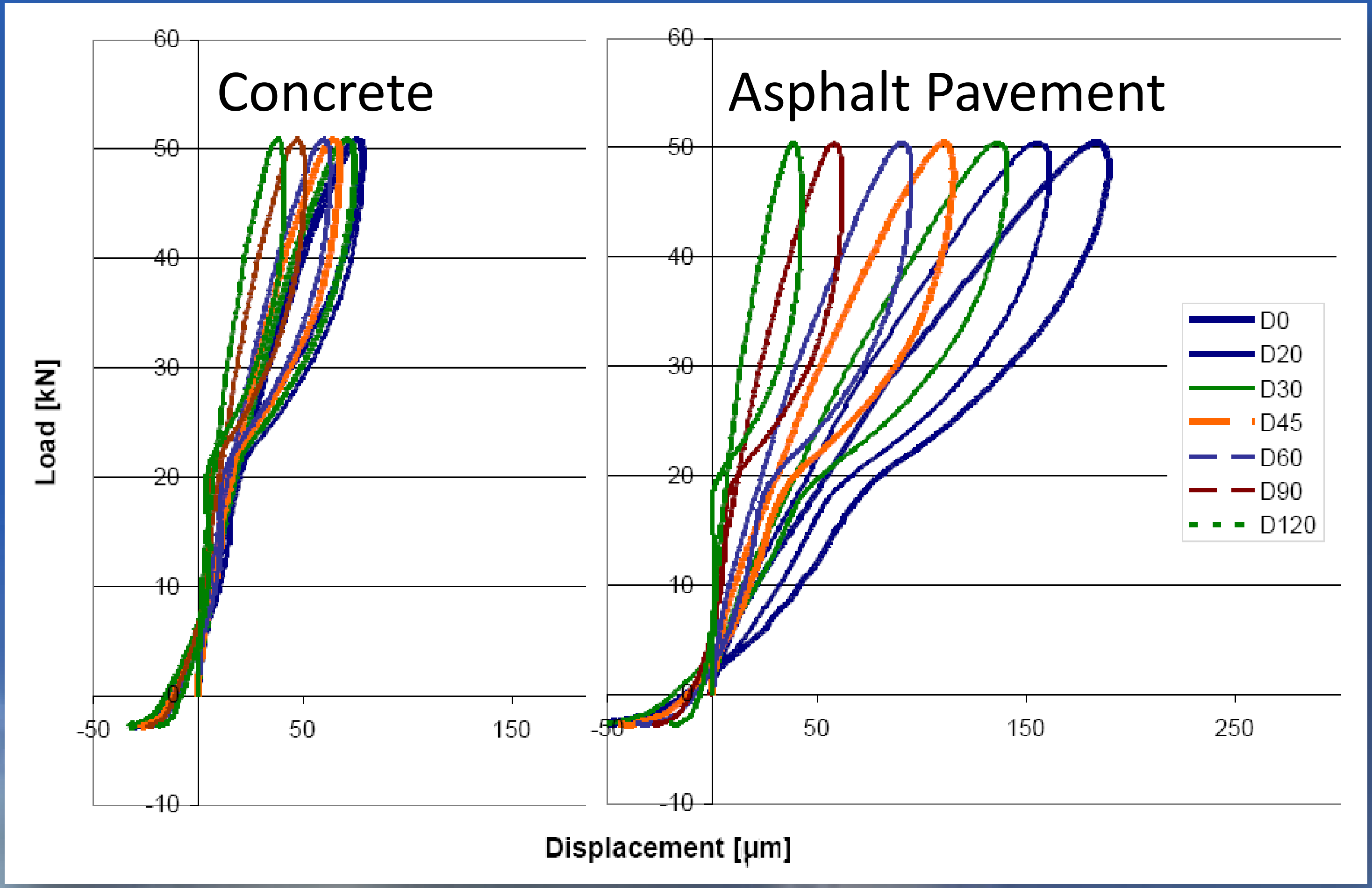


Hysteresis effect
Energy Loss during load/unload





Benbow et.al.(2007) Lab Study at TRL, indicated a positive effect of stiffness; however, the effect was not statistically significant.

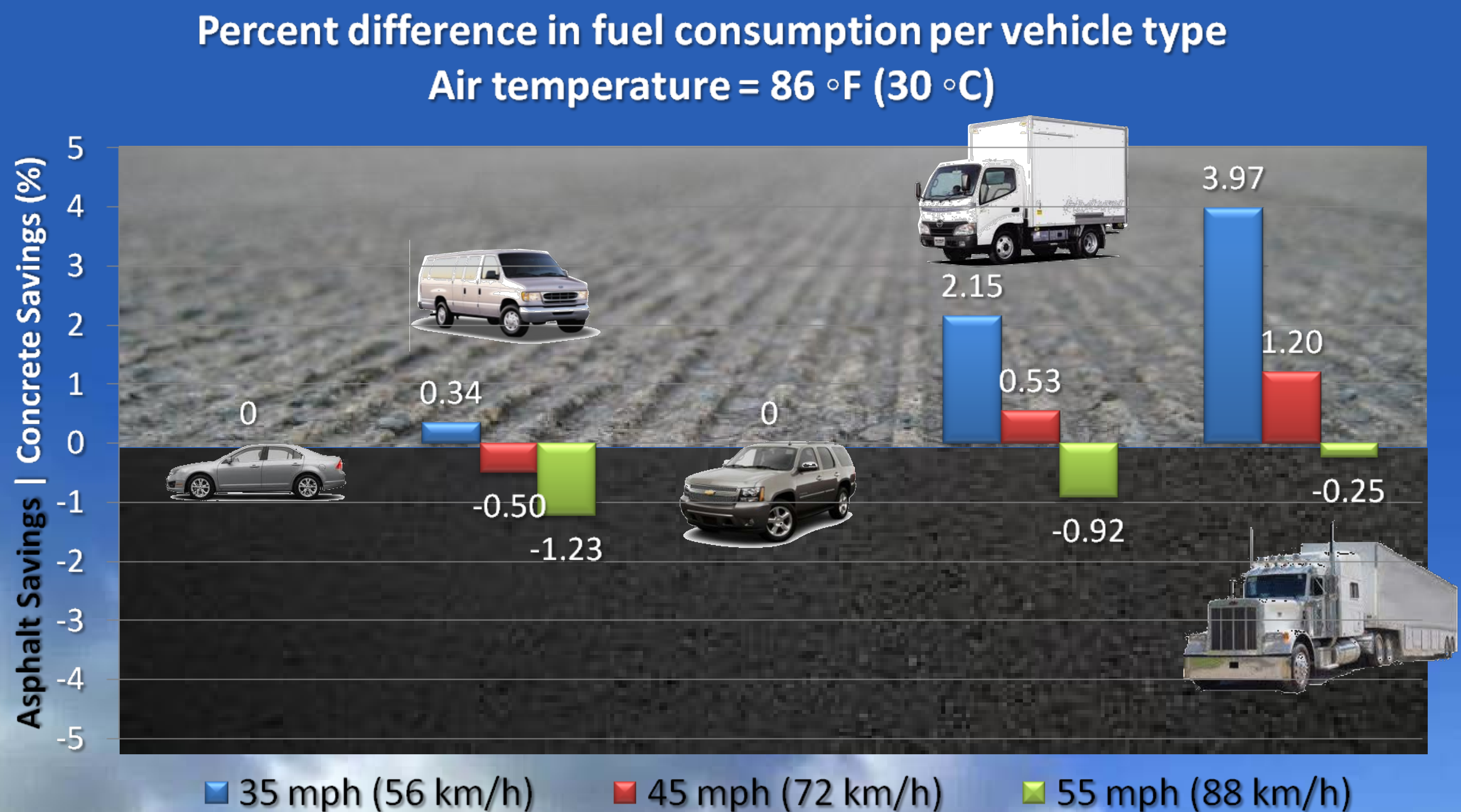


Hysteresis effect measured with a Falling Weight Deflectometer (FWD) on a concrete pavement (left), compared to an asphalt pavement (right)

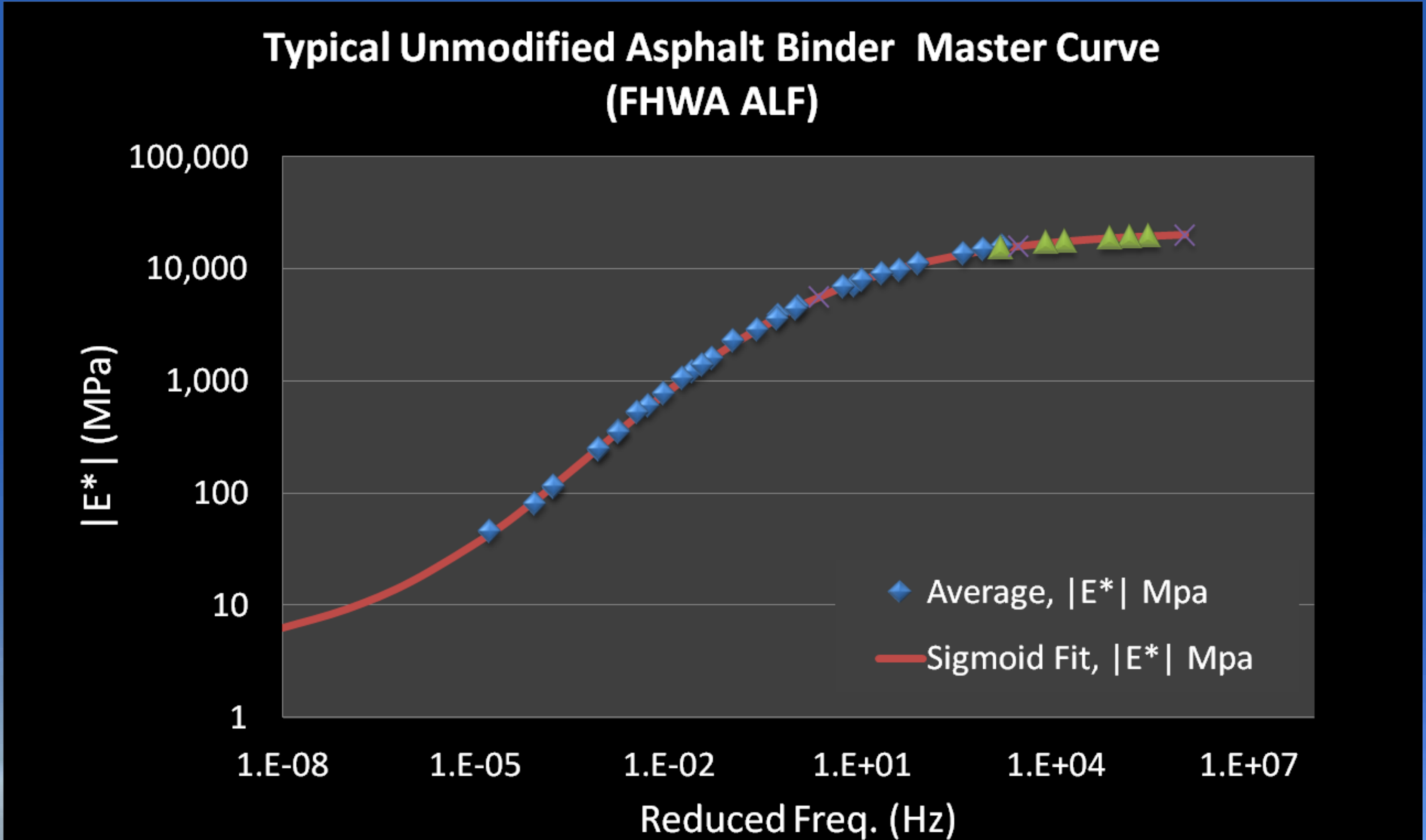
However… NCHRP 1-45 VOC Model

All Things Equal *(Similar in concept to MIT)*

IRI = 95 in/mile, MPD = 0.05 in, 80°F

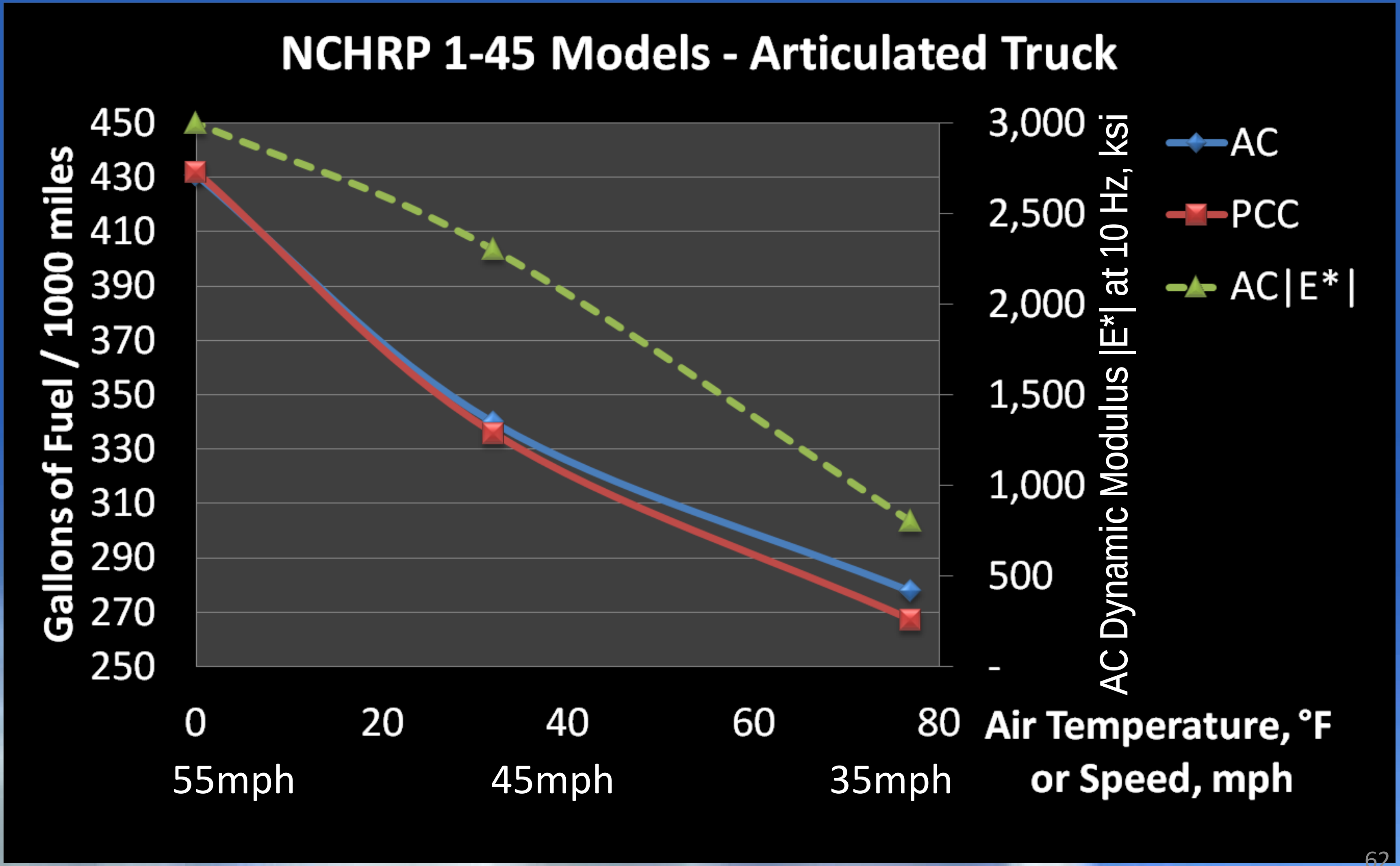


NCHRP 1-45 Model does not appear to address AC Stiffness Adequately



Special Thanks to Dr. Nelson Gibson

1-45 Model Fuel Consumption for Asphalt & Concrete




Smoothness

State Data Collection

Smoothness Data for HPMS

Questions?			Concern
Who is collecting the data?	~¾ State DOT	~¼ Contracted Out	Some
Daily Calibration	We think ~ ½ do		Yes
Certification	We think > ½ do	Some RR Testing	Yes
Sampling Frequency	½ Network each yr	Changing to annual	Some
Sampling Rate(*)	Unknown	From 1" to 13"	Yes
Independent Assurance	None		Yes
Material Effects (PCC)	Not accounted for in data collection		Little

Network Level: High-Speed Inertial Profilers (HSIP) at posted speed limits
Project Level: Light-Weight IP (Golf Cart, John Deere Gator), ULIP
Calibration: check accelerometer/laser, benchmark w/ known IRI, DMI
Certification: to reference roadway surveyed

(*) Proposed AASHTO R43 will standardize it 1" with 300' wave-length limit

NHS Scenario

- Analysis Period = 30 years
- 2-way $AADT_{24hour}$ ~ 29,800 vehicles/ day
- 29% Trucks *(Total Rural Interstate - IDOT)*
- 36% Passenger Vehicles
- 35% Lt. Wt. Trucks (including SUV's)

- 80 million Total Design ESALs (2,680 kESAL/yr)
- Project Length is **25 miles**

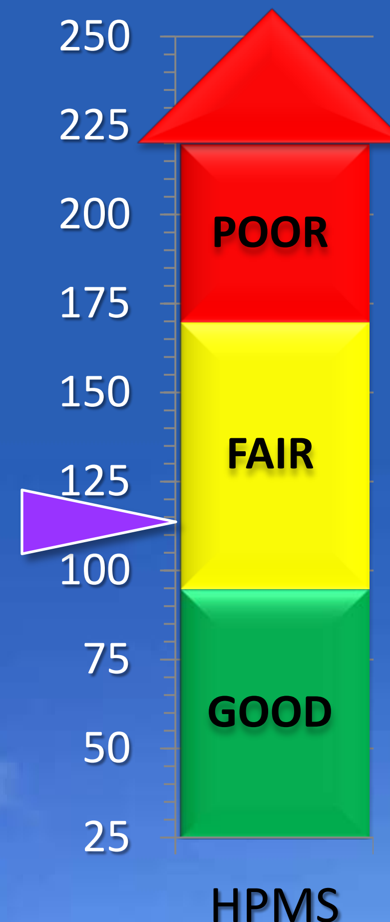
ACPA

Ottawa, Illinois

Source IDOT 2009 ADT

Comparison Section Glooptonite™

- Constant Surface, *"Fair Condition"*
  - IRI = 112 inches/mile
    1.77 m/km
  - MPD = 0.900 mm



GPS-1 (AC) IRI Model

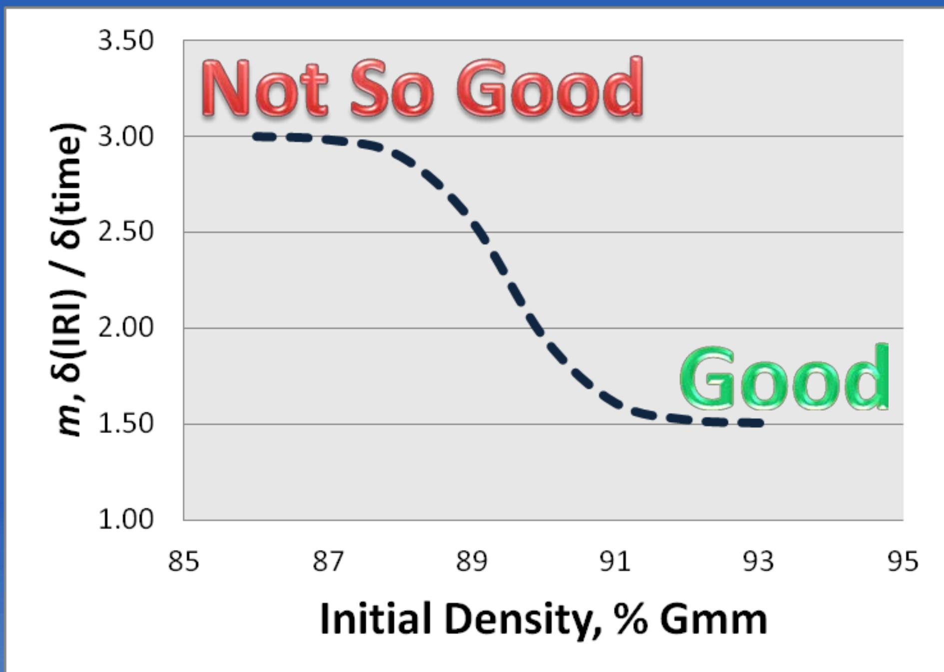
- $IRI_{(t)} = -0.143 + 1.0765(IRI_0) + 0.0424(\delta\ Time) + 0.0094(Traffic^{1/2} / SN^5) + 0.0012\ (\delta\ Time\ *PL) + 0.006(\delta\ Time\ *\ BaseP200)$

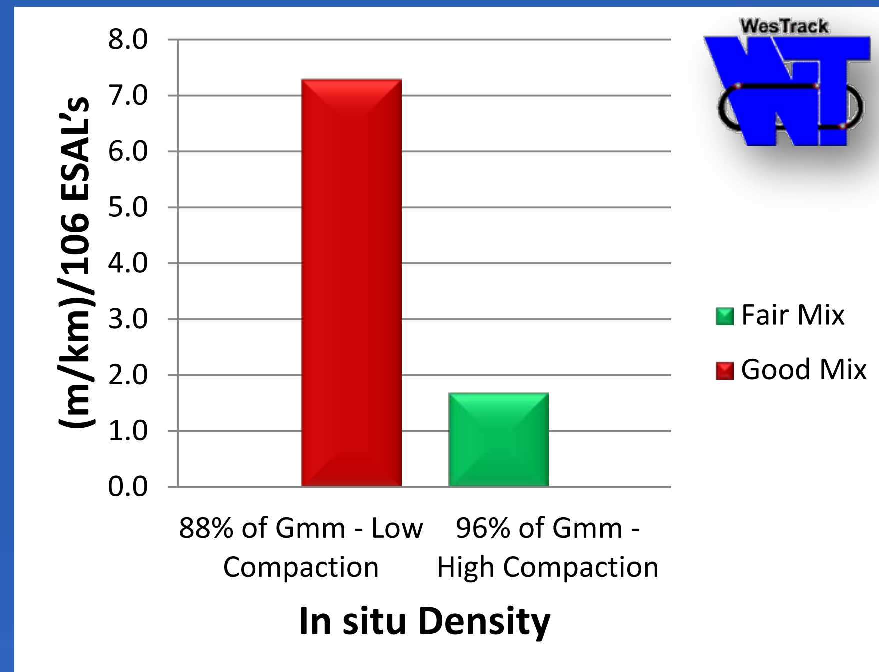
- Based on 168 sections
- 40% of the GPS-1 sections were deassigned
  - Deassignment due to owner agency overlay
  - Average age at deassignment – 15 years
  - Average IRI at deassignment – 107 in/mile


LTPP Data Analysis: Factors Affecting Pavement Smoothness

From a Materials Perspective

Future Ph.D. Topic





$$m(IRI_{t=0}) = m_{min} + m_{range} \frac{1}{(1 + e^{-\alpha})}$$

$$\alpha = -6 + (-12/G_{mm\text{-}range})*(G_{mm\text{-}initial} - G_{mm\text{-}min})$$

SPS-9: Validation of SHRP Asphalt Specification and Mix Design – *Superpave®*

- Simplified IRI Model for Superpave (Interstate)

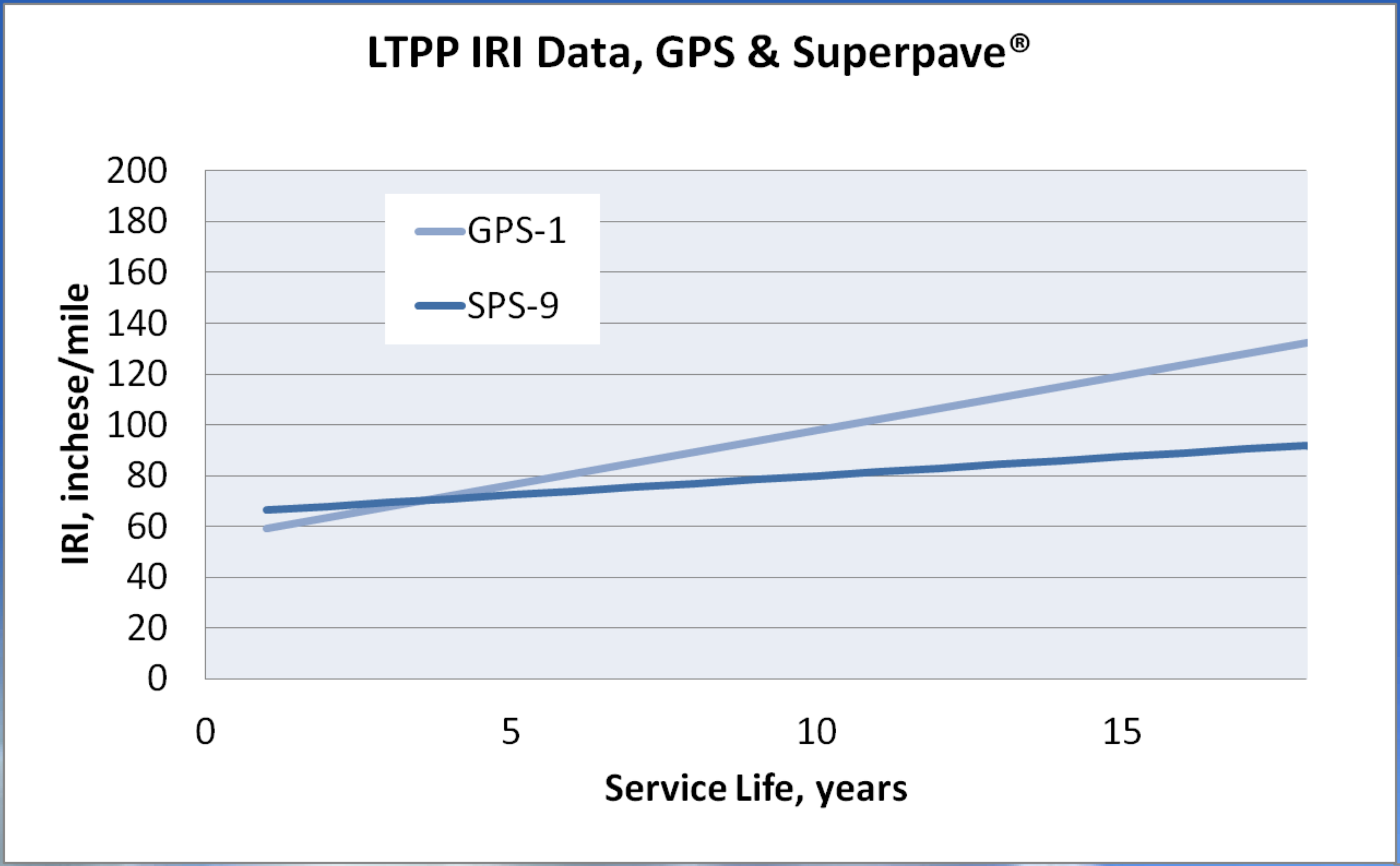
$$IRI_t = IRI_0 + 1.4\ \text{Time (yr)},\ \textit{in/mile}$$

$$IRI_t = 65 + 1.5\ t\ \textit{(Scenario), year 1 to 18}$$

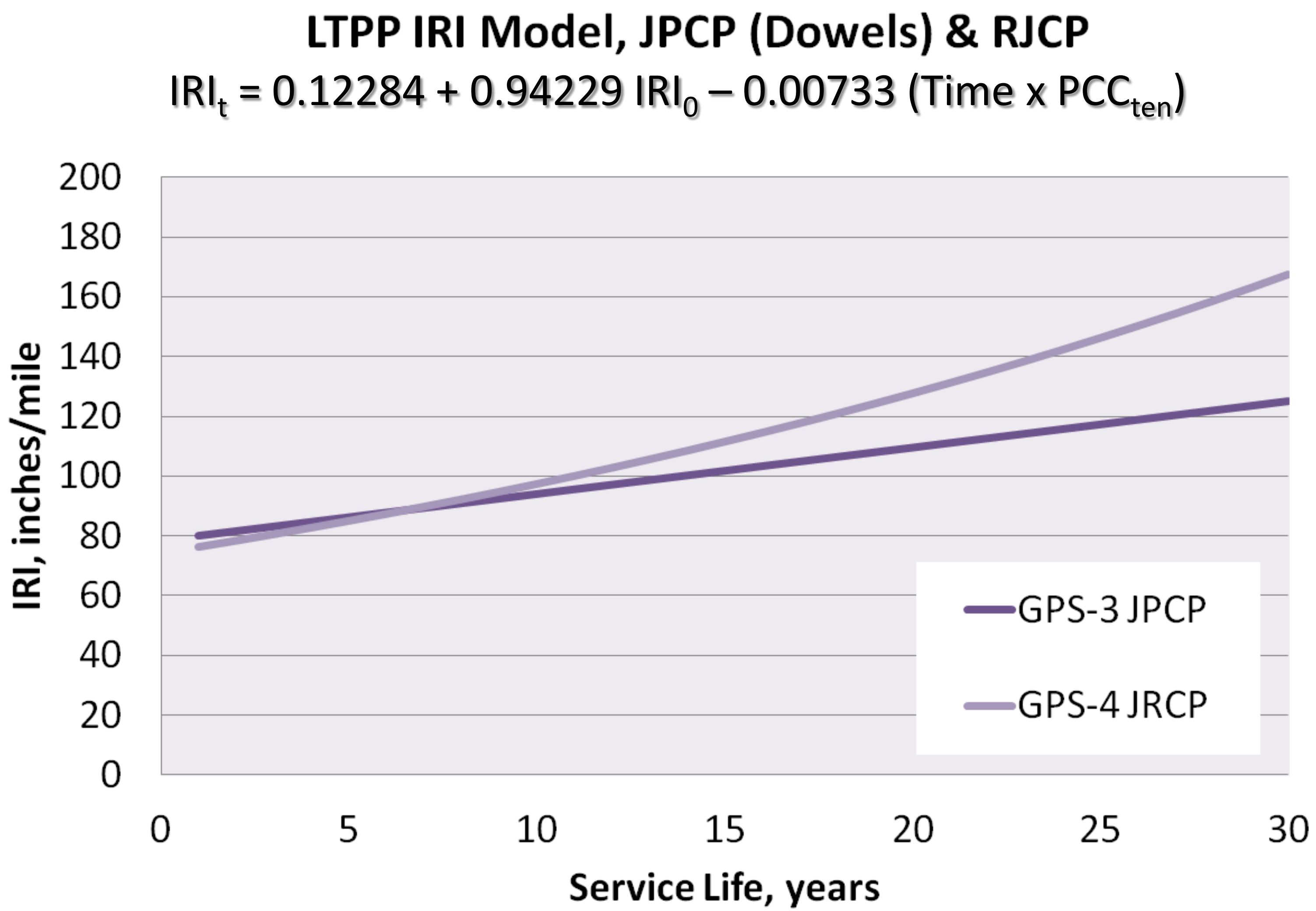
$$IRI_t = 85 + 1.8\ t\ \textit{(Scenario), overlay @ 18+}$$

Road Type	n	IRI_0	Slope, δIRI/yr
Interstate	7	49	1.4
US Route	7	68	0.8
State Road	2	62	0.4

LTPP IRI Models
AC Sections (GPS-1 & Superpave®)



LTPP Data - Concrete
GPS-3 (JPCP) – Doweled & GPS-4 (JRCP)

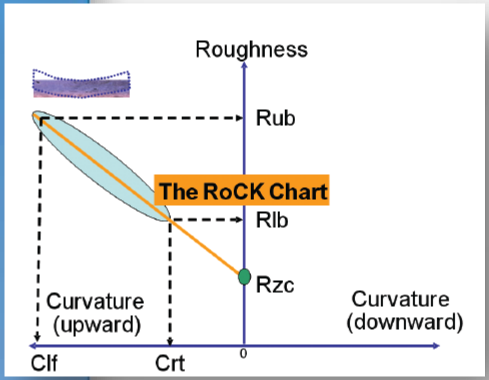


Not Considered… Yet

TechBrief

JULY 2010 | FHWA-HIF-10-010

Our understanding of concrete pavement roughness has advanced considerably…



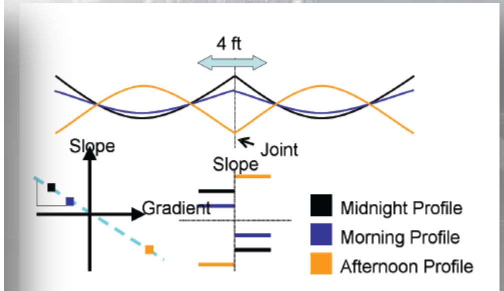


FIGURE 6. Joint functionality analysis showing diurnal effects.

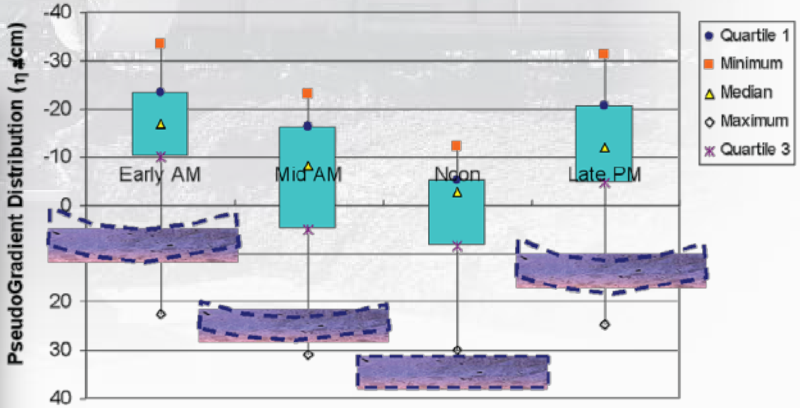


FIGURE 4. Diurnal curvature analysis. Example of a box plot for a test section where most of the slabs are curled up.

Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance

Potential Impact

Curling and Warping is a function of..

- CTE of the concrete
- Weather Conditions
  (esp. cloud cover, temperature)
- Joint "Freedom"
  (function of width, joint reinforcement, etc)
- Some sites fluctuate as much as **40 in/mile ½ Car IRI**
  ~ 11% Δ in RCC_{MIRIAM} or 3.4% Δ in fuel/emissions
- Others around **10 in/mile** (from day to night)

Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance

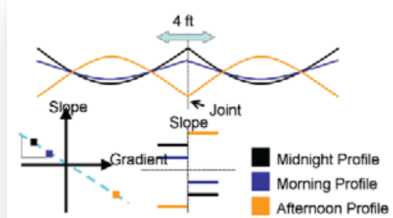


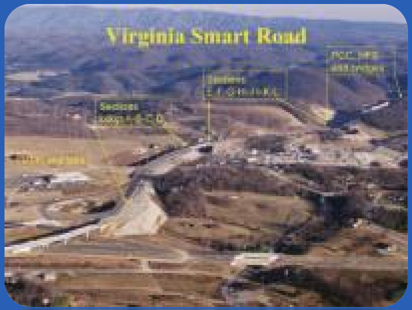
FIGURE 6. Joint functionality analysis showing diurnal effects.

What about Texture?

Data Gaps

- Megatexture Texture Data:
  - US currently does not collect texture on a project or network level on roadways

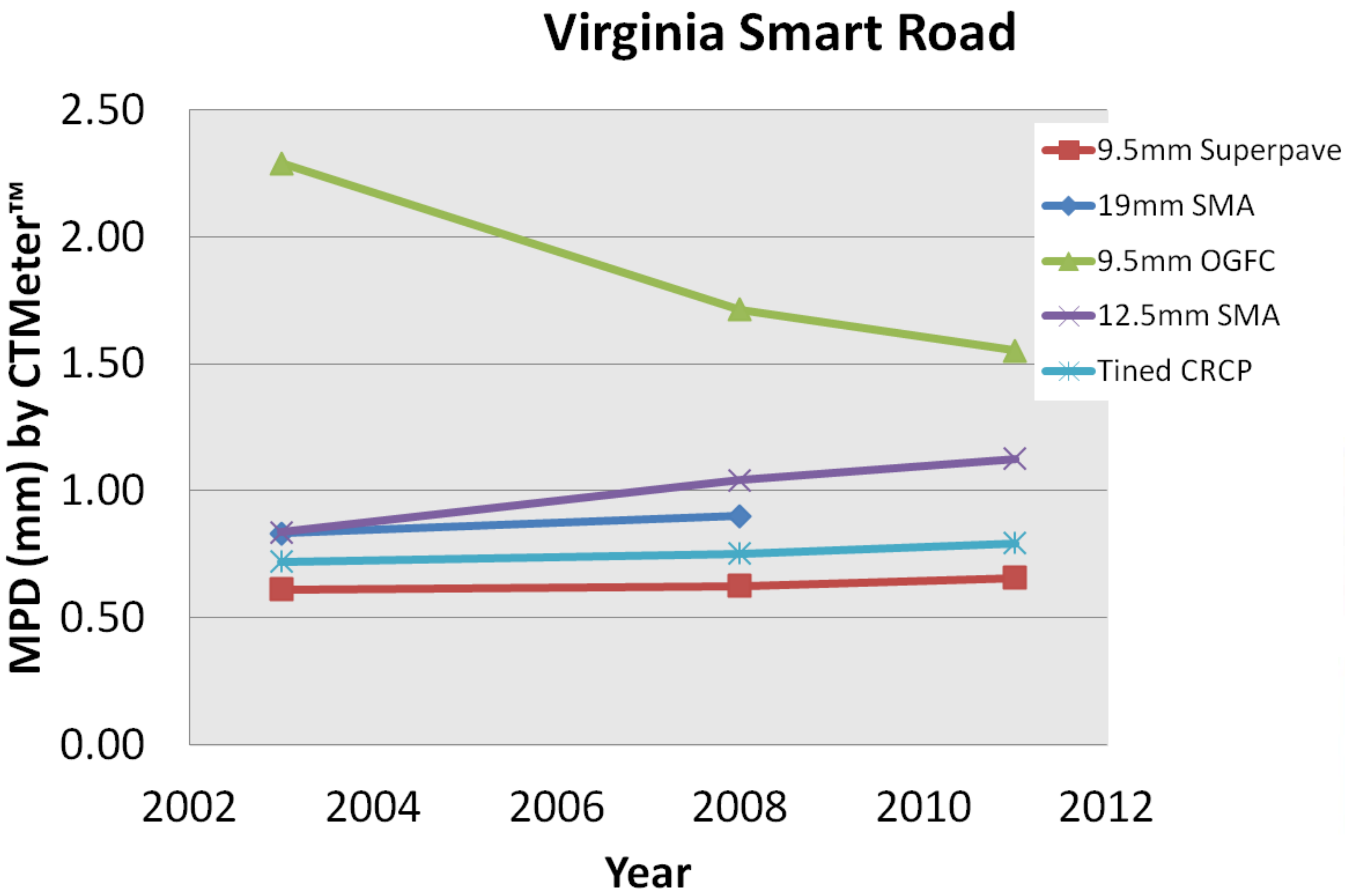
Texture *f*(time)



- Macrotexture, MPD *(mm)*
  - Static Method (CTMeter)
- Data Sources:
  - LTPP, CT SPS 9
  - Virginia Smart Road, *Environmental Effects Only*
  - NCHRP 634, Long. Textured Concrete Pavement
  - NCAT Test Track
  - Future FHWA PCC Study
  - Future FHWA LTPP

Environmental Impact

Special Thanks to Edgar de León Izeppi



SM 9.5 D SuperPave

SMA 9.5 D

OGFC

Tined CRCP

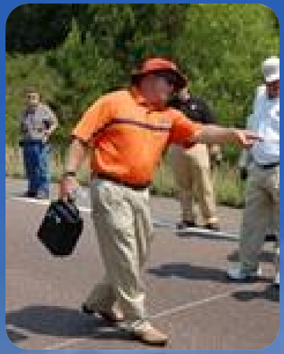
2009 CT DOT
LTPP SPS 9 Sections,
Constructed in 1998 (t = 11 years)

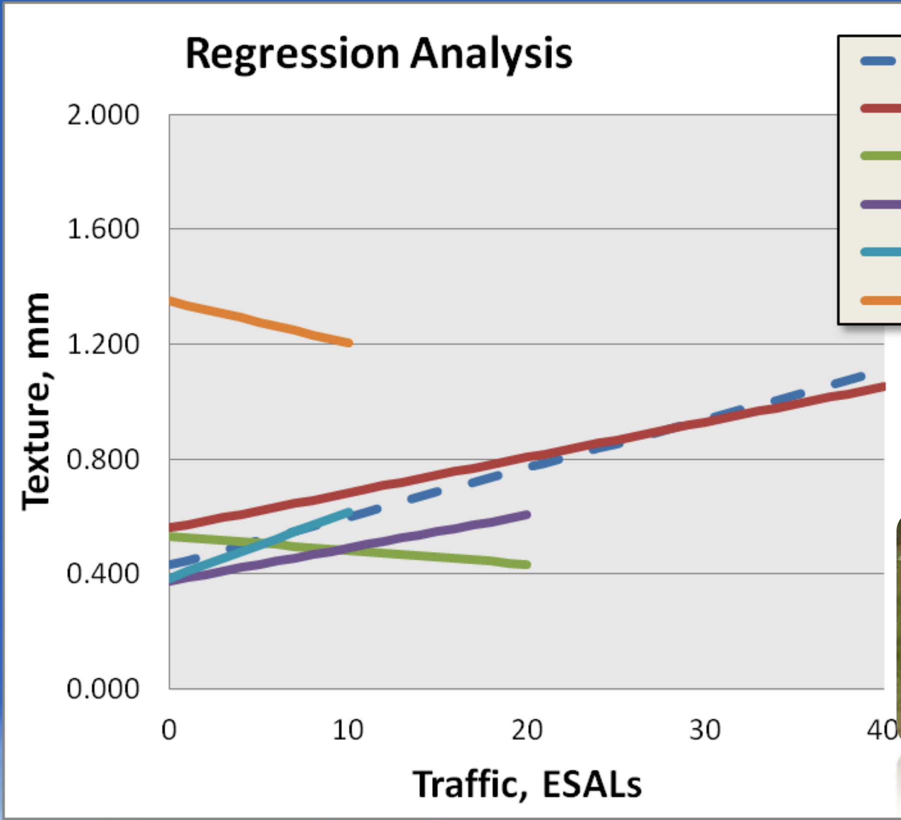
LTPP SPS 9 Section ID	Average MPD (CT Meter), mm
090901	0.81
090902	1.04
090903	0.91
090960	1.02
090961	1.27
090962	1.32
Average	1.06

2012 Harman Analysis

Test Track 2003 to 2010 Superpave Mixes

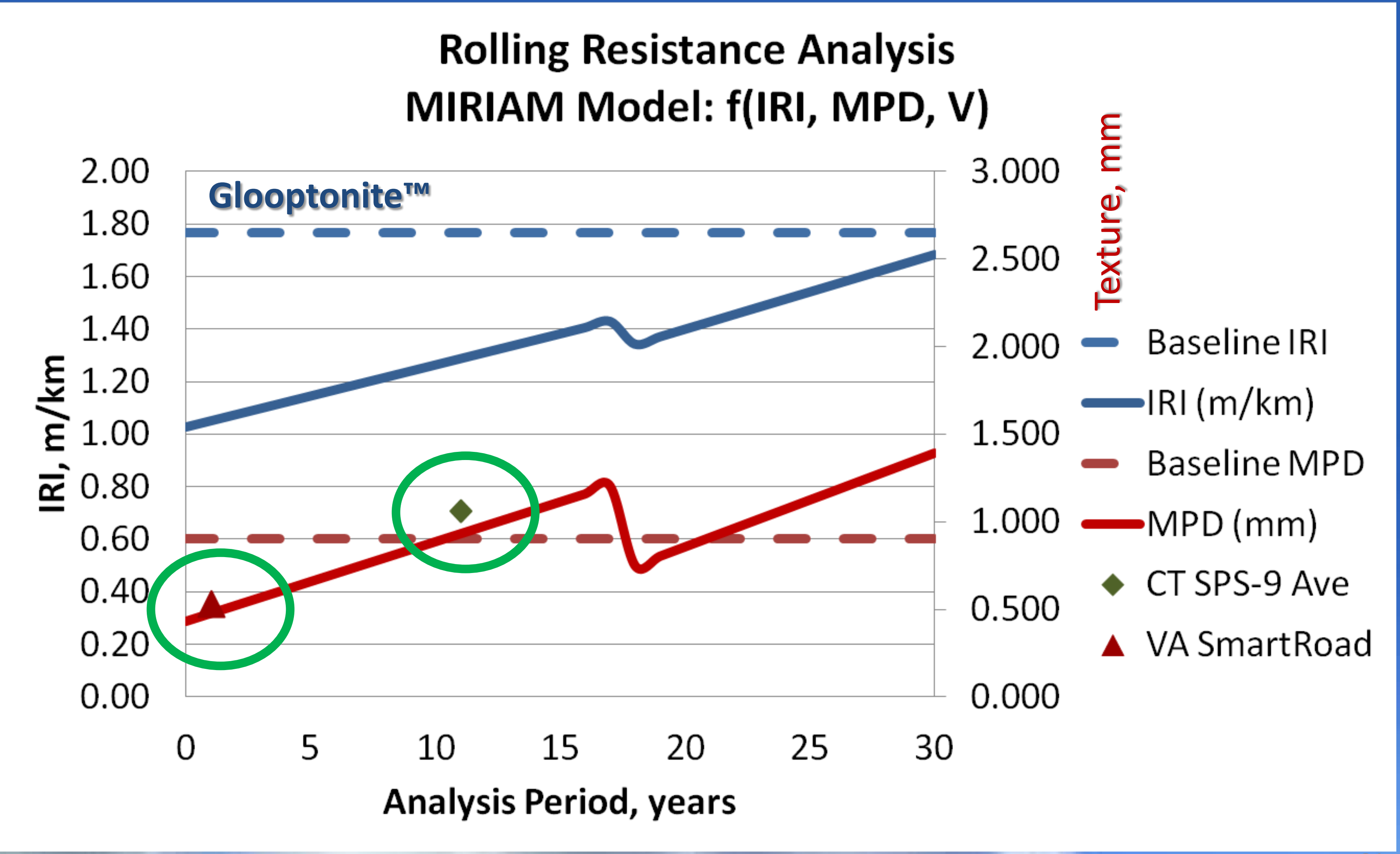
- 16 Sections
- PG 67 & PG 76
- HMA / WMA
- 0 to 50% RAP
- 10 to 40 m ESAL's





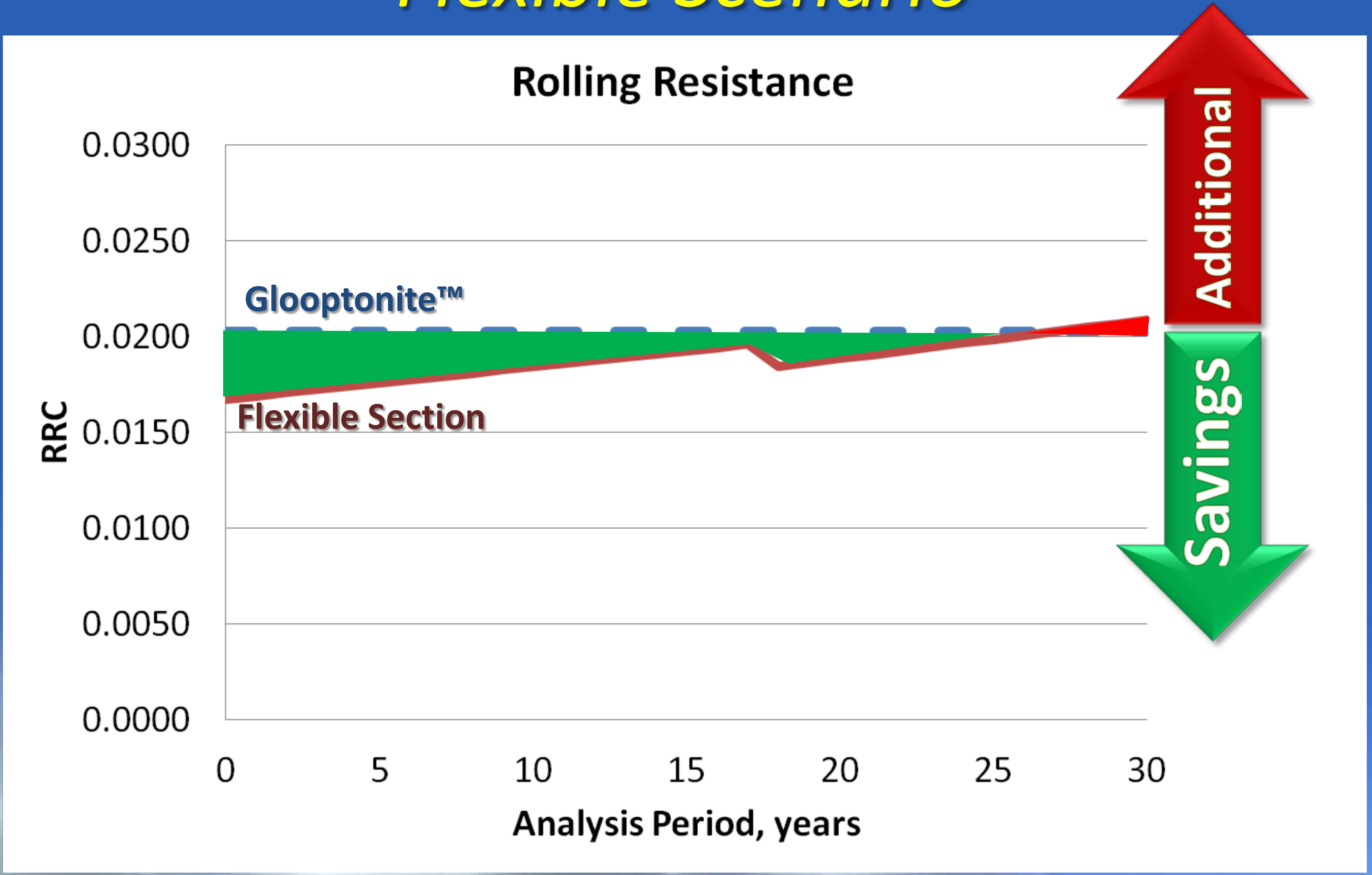
- Ave. Initial Texture (mm) = 0.431
- Ave. Change (δMPD / δmESALs) = 0.017, ranging from -0.015 to 0.023
- Average R^2 = 0.70

RR Inputs based on
SPS-9 IRI and NCAT Texture Model, Overlay at year 18



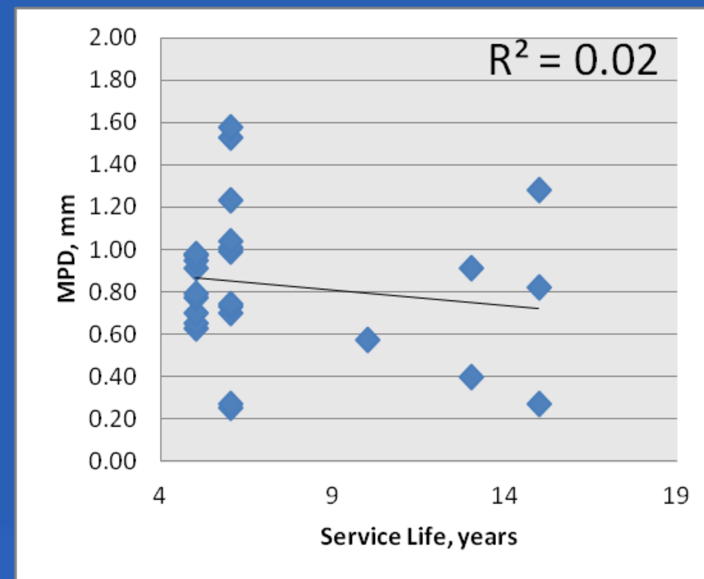
MIRIAM RRC *f*(IRI, MPD)

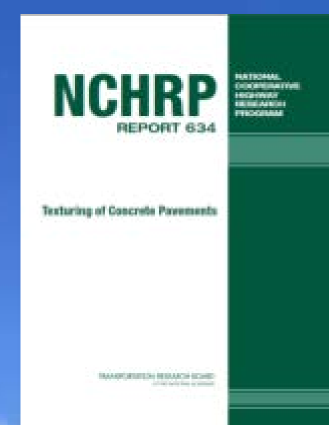
Flexible Scenario



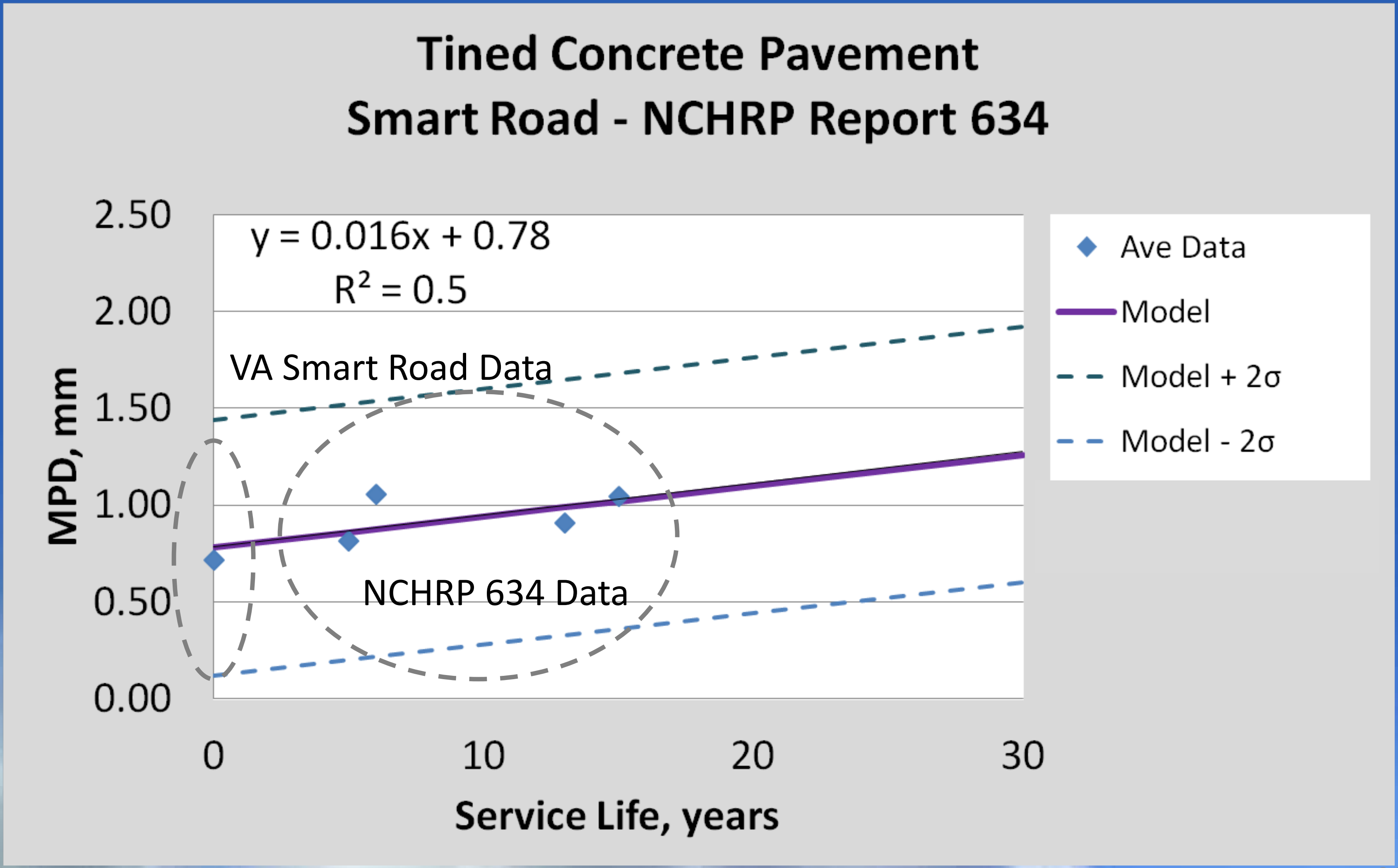
Texturing of Concrete Pavements
NCHRP 634 – 2009 Report

Parameter	Value
No. of Sections	38
No. of States	7
Ave. Service Life	7.7 years (5 to 15)
Ave. MPD	0.80 mm
Min. MPD	0.25 at 6 years
Max. MPD	1.58 at 6 years
Range MPD	1.33 (166% of Ave.)
St.Dev. (s)	0.299

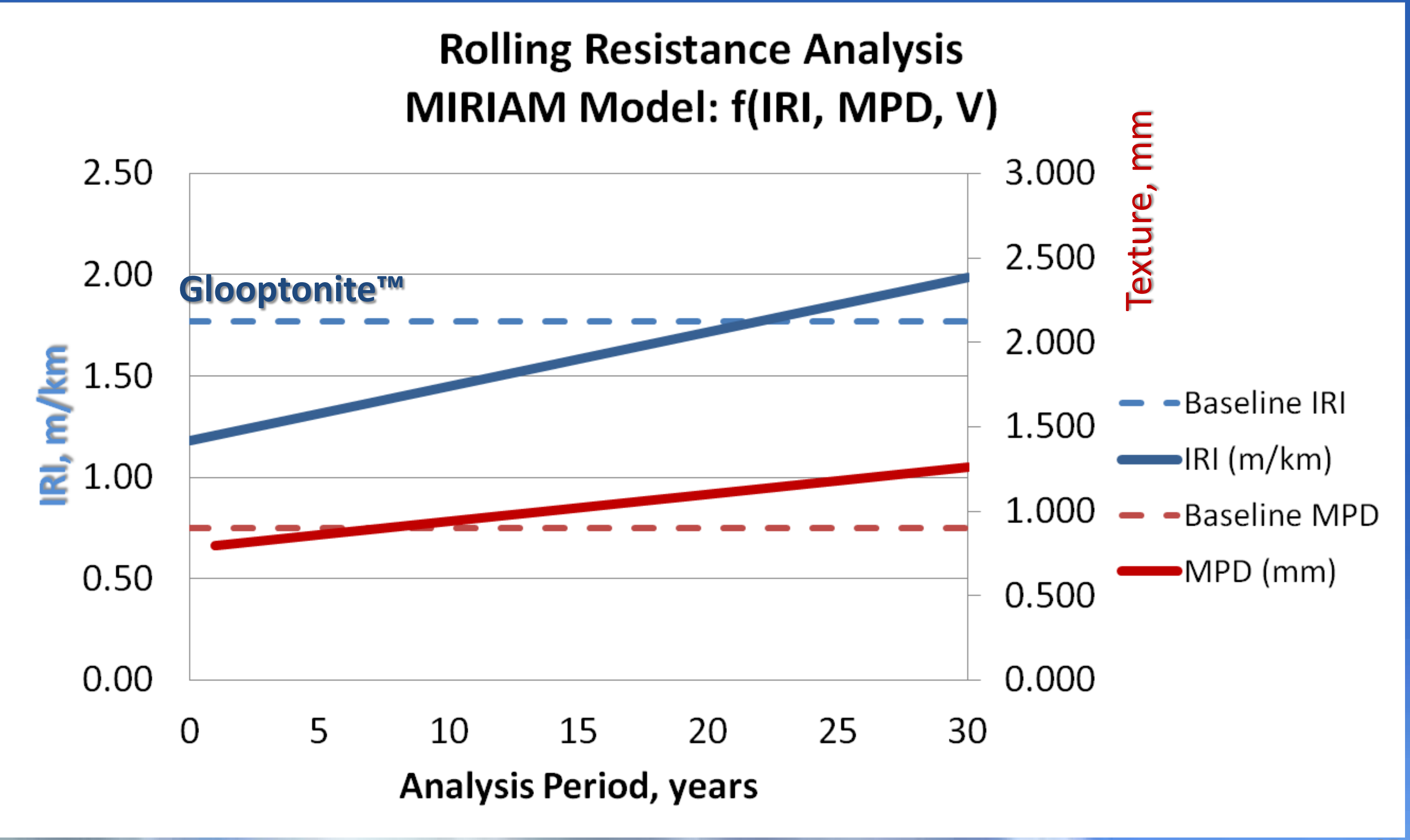




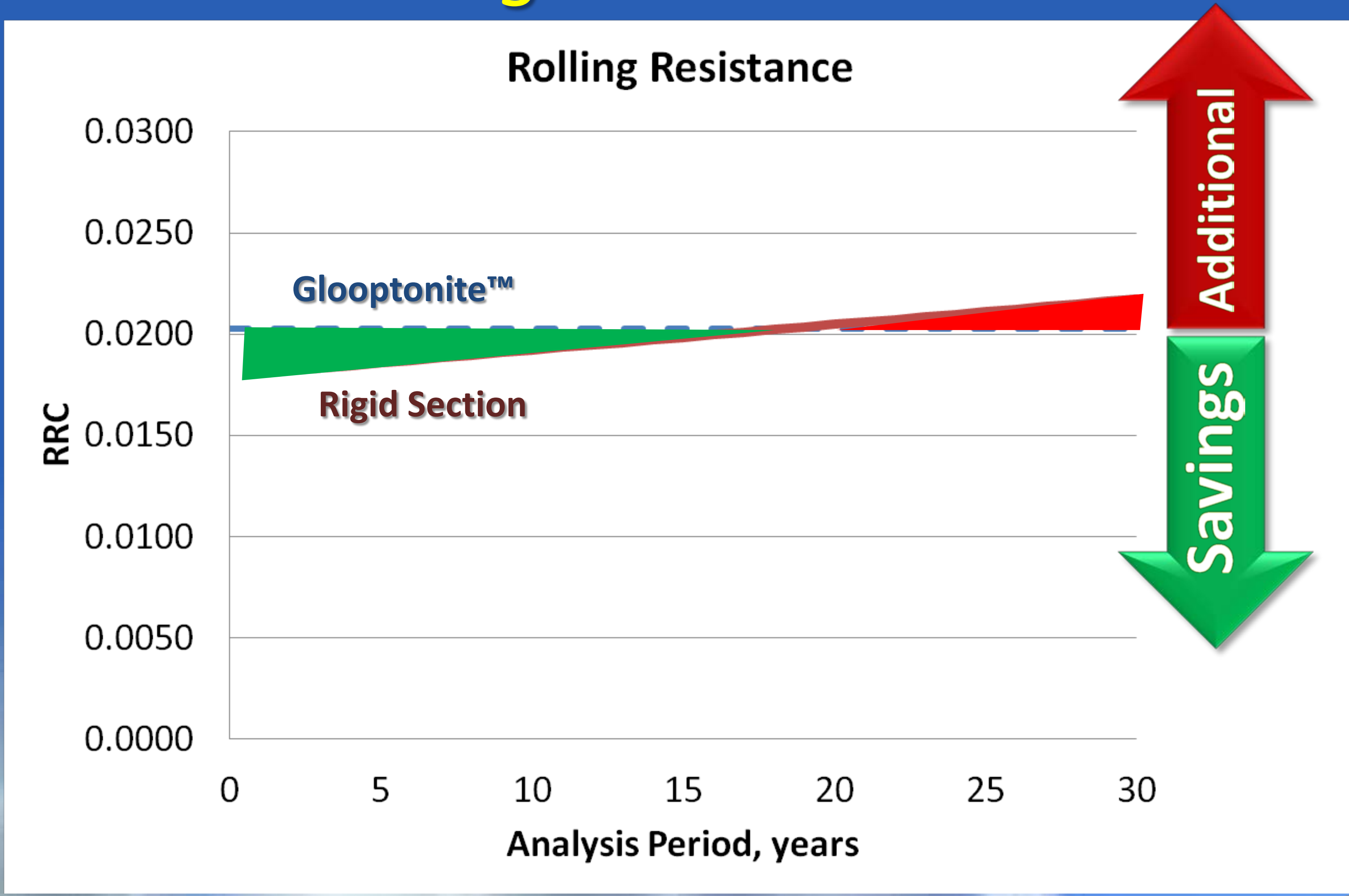
Basic Model for Tined Concrete Pavement *(Harman PCC_{Tined} Texture Model)*



RR Inputs based on
GPS-3 IRI and Harman PCC_{Tined} Texture Model

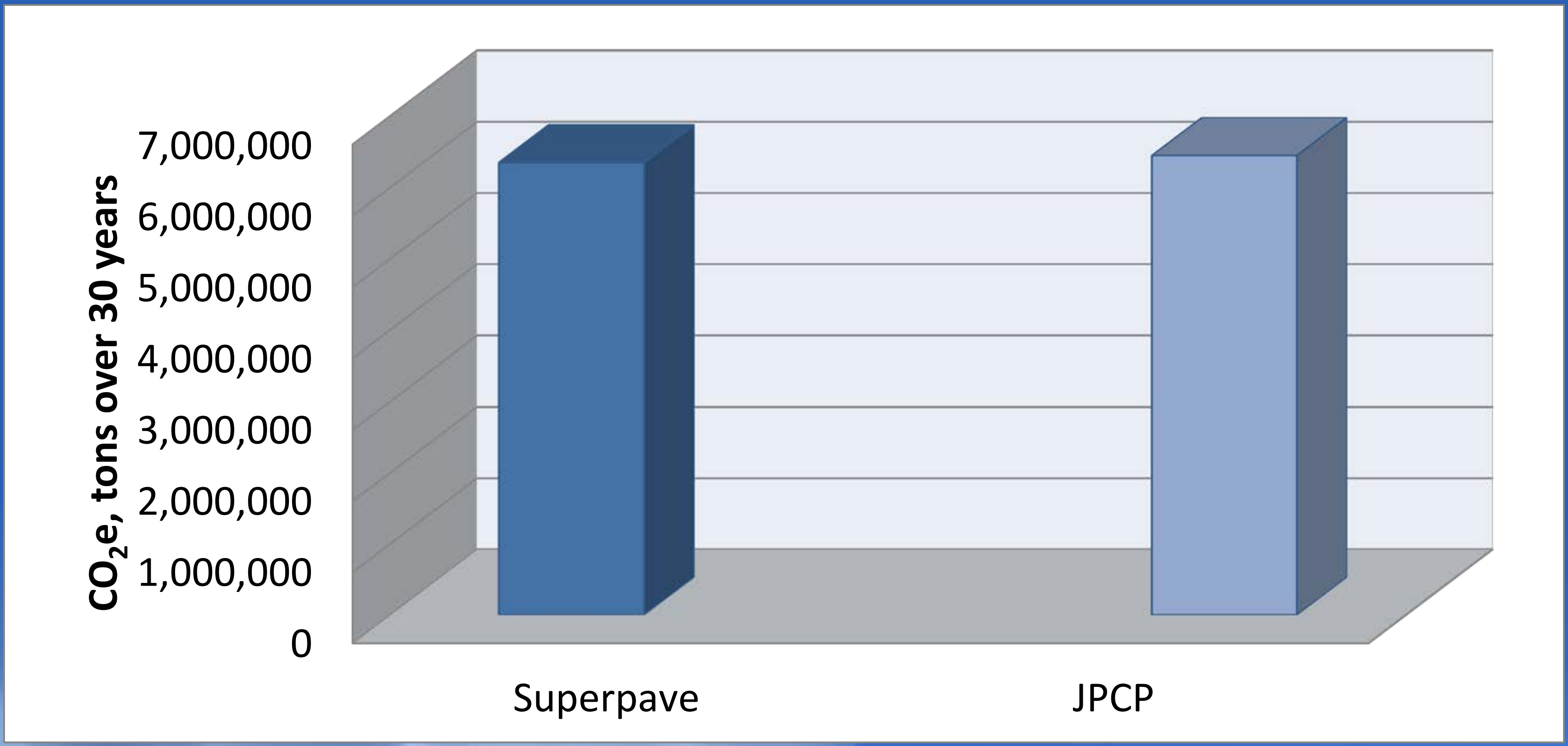


MIRIAM RRC *f*(IRI, MPD)
Rigid Scenario

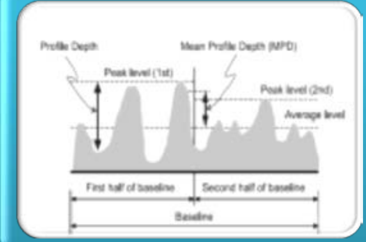


- The purpose of the presentation is to demonstrate how these analysis tools can be used (period)
- It is not to compare Superpave SPS/Test Track Sections ***to*** LTPP GPS Concrete Sections.

Accounting for IRI/Macrotexture (MPD) Within 2% of each other



IRI / MPD MIRIAM RRC Model

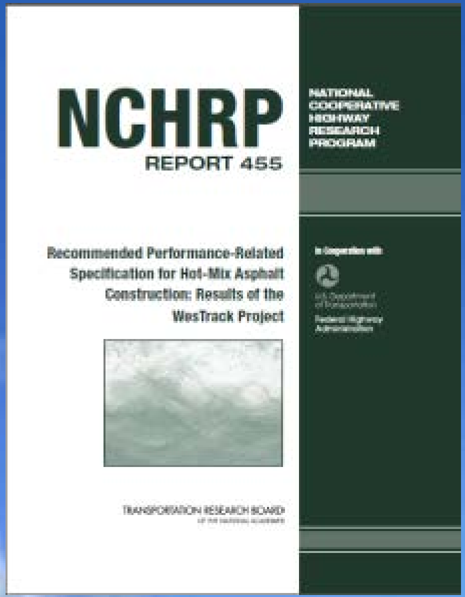


- $RCC = C_1 + C_2 \; MPD + C_3 \; IRI + C_4 \; IRI \; (V - V_{ref})$

WesTrack Fuel Consumption

"Pavement roughness had a significant impact on fuel consumption of trucks applying loads to WesTrack pavement test sections. Under otherwise identical conditions, trucks used ***4.5 % less fuel*** *on smooth (post rehabilitation) than on rough (pre rehabilitation) pavement."*

- NCHRP Report 455, p. 483



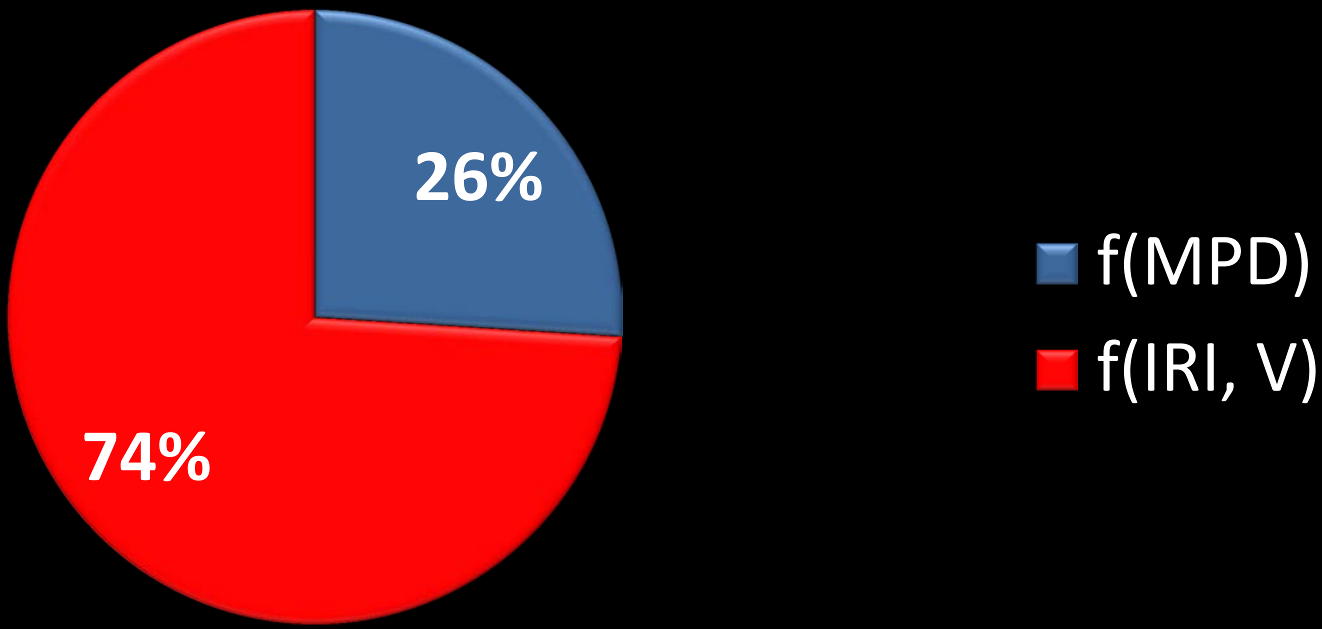
Summary of MIRIAM Models Similar to WesTrack (4.5%)

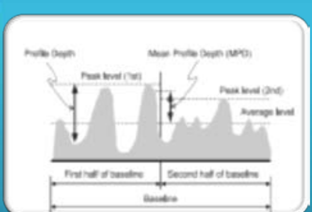
Impact of Good to Poor	Impact
Flexible Scenarios	5.0%
Rigid Scenarios	4.9%

MIRIAM Model Breakdown

Example Concrete Section 30 year Period

Contribution of Macrotexture (MPD) and Ride (IRI)

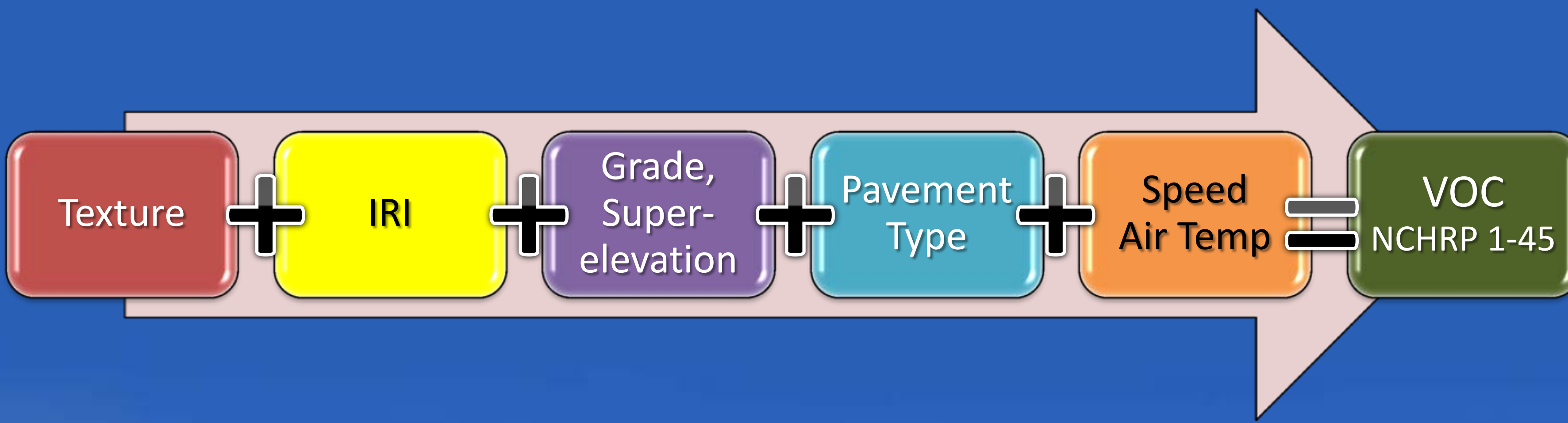




IRI / MPD MIRIAM RRC Model

- $RCC = C_1 + C_2 \; MPD + C_3 \, IRI + C_4 \, IRI \,(V - V_{ref})$

NCHRP 1-45: Effect of Pavement Conditions on VOC Within 0.4% of each other



NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP 1-45 VOC Models

- Partial Costs – Fuel Consumption ONLY
- Not included: Tire wear, repair & maintenance

Summary of Modeling

Analysis Method	Delta
MIRIAM *f*(MPD, IRI, V)	2%
1-45 VOC Models @ 77°F / 55mph	0.38%

2009 NHS

- 40% of All Traffic
- 75% of All Freight Traffic

Condition	Mileage of NHS	~Miles Traveled	Sustainability $CO_2e^{(*)}$
Poor IRI > 170 in/mile	8%	11%	8% *additional*
Fair	66%	69%	*Net 0%*
Good IRI ≤ 95 in/mile	26%	20%	3% *savings*

- (*) – compared to Glooptonite™ with MIRIAM

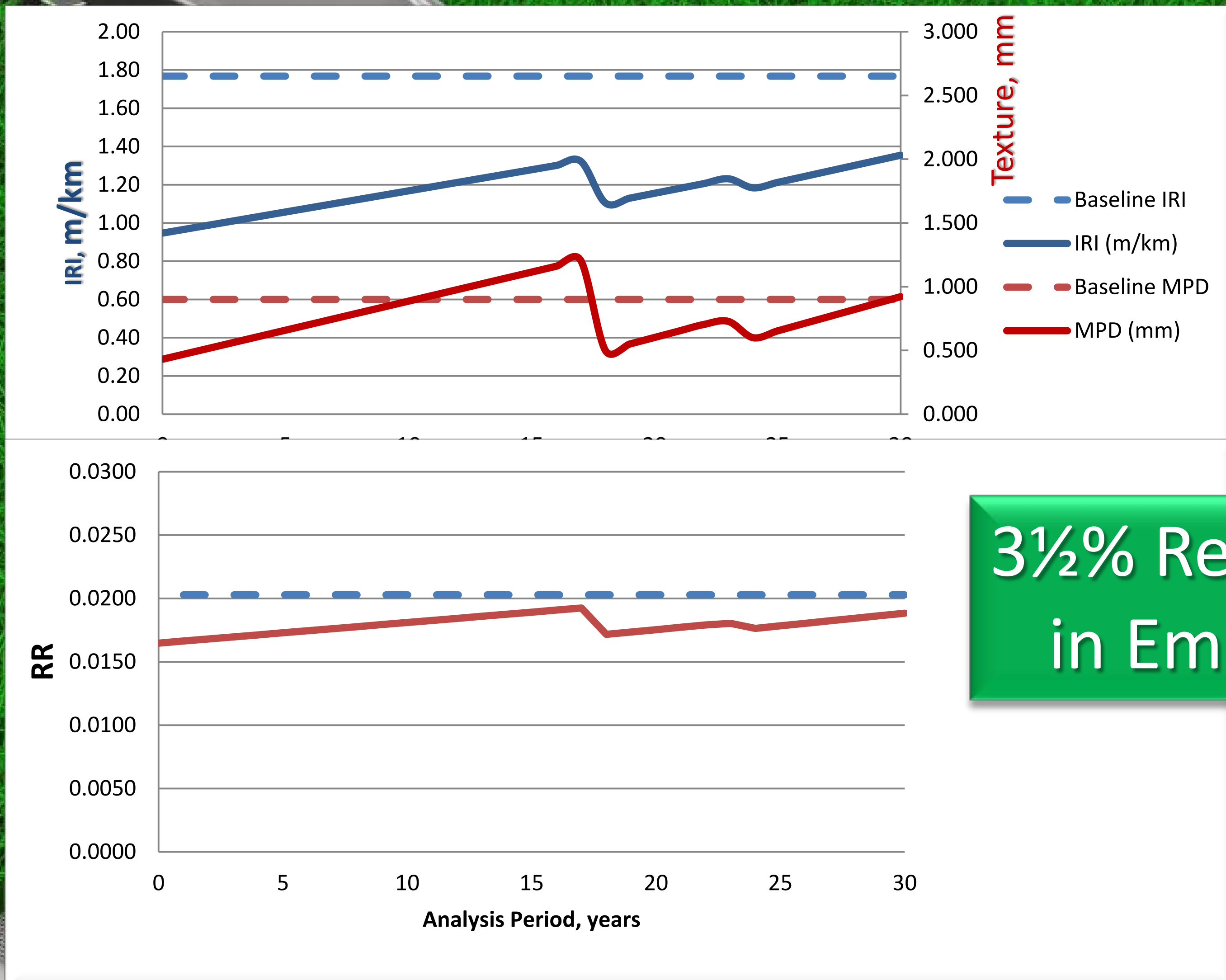
Simple Math

- If Fair is similar to Glooptonite™, and
  - 11% miles traveled generates 6% additional, and
  - 20% of miles traveled generates 3% less…

Net: +11%(8%) – 20%(3%) < ZERO (-.3%)

Poor ***Good***

Potentially Powerful Tool for assessing **Pavement Preservation**

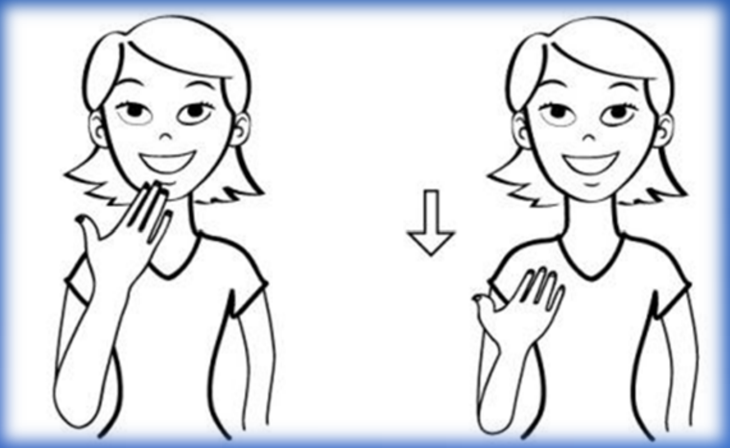


3½% Reduction in Emissions

Where are the greatest potentials, within our control, for reducing environmental impacts???

Special Thanks

- Bob *"Mr. Smoothie"* Orthmeyer (RC)
- Larry Wiser (LTPP)
- Nadarajah "Siva" Sivaneswaran (R&D)
- Gina Ahlstrom (HQ)
- John Bukowski (HQ)
- Nelson Gibson (R&D)
- Randy West (NCAT)
- Buzz Powell (NCAT)
- Gerardo Flintsch (VTTI, VA Smart Road)
- Imad Al Qadi (University of Illinois)
- Karim Chatti (MSU)



THANK YOU

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