Quantifying Environmental Impacts of Pavements

U.S. Department of Transportation
Federal Highway Administration

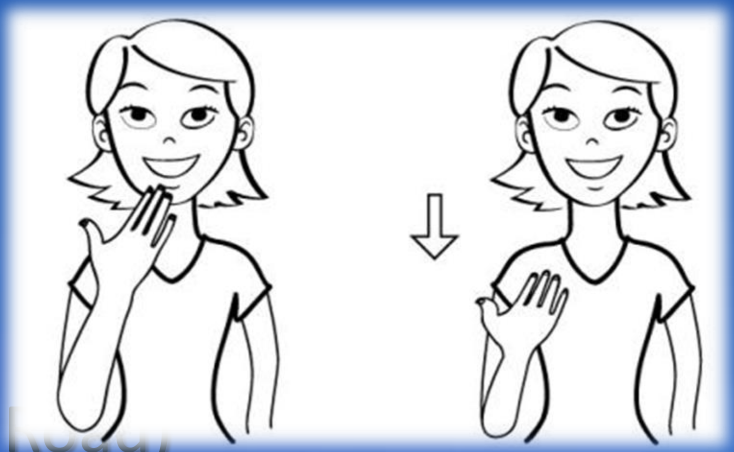
Annual Conference
March 26-27, 2013
Mount Pleasant, MI

Asphalt Pavement Association of Michigan

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

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)
- Jim Musselman (FL DOT)

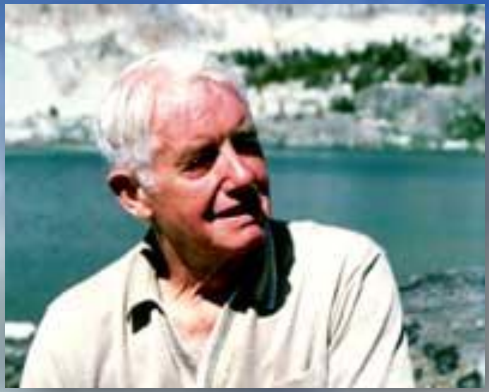


Preamble

David Brower,

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

The environment is very important!



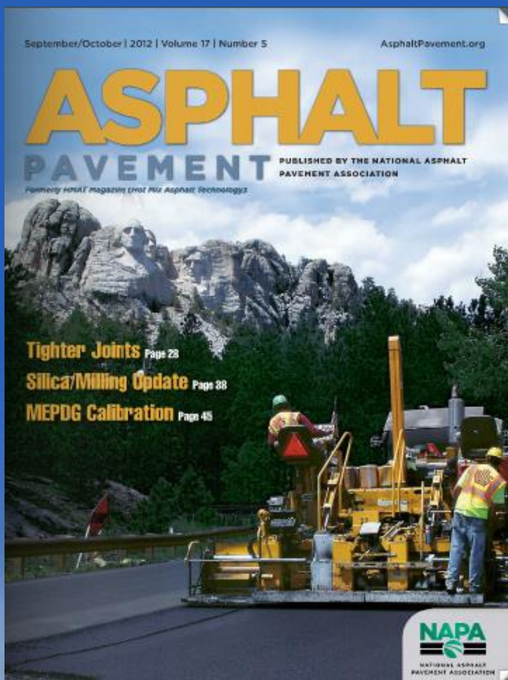
" If you can't measure it, you can't manage it."

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."*

Quick Reference for You

September/October |2012|Volume 17 | Number 5



[Hyperlink](#)

A Historical Perspective…
Customer Service

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

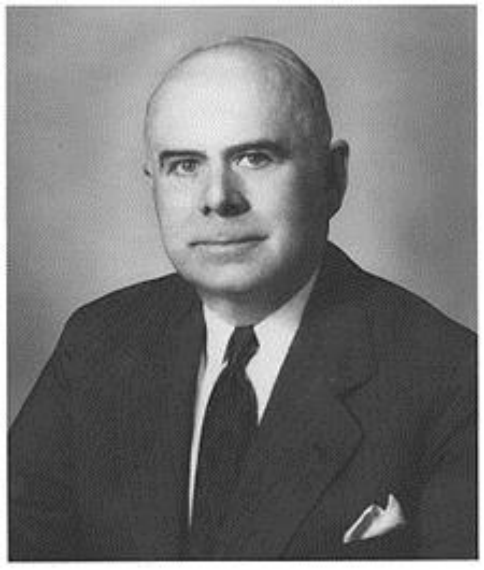
Community Needs *(Local to National)*

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

Economics *(LCCA, Commerce, Growth)*

Ride *(Smoothness, Texture)*

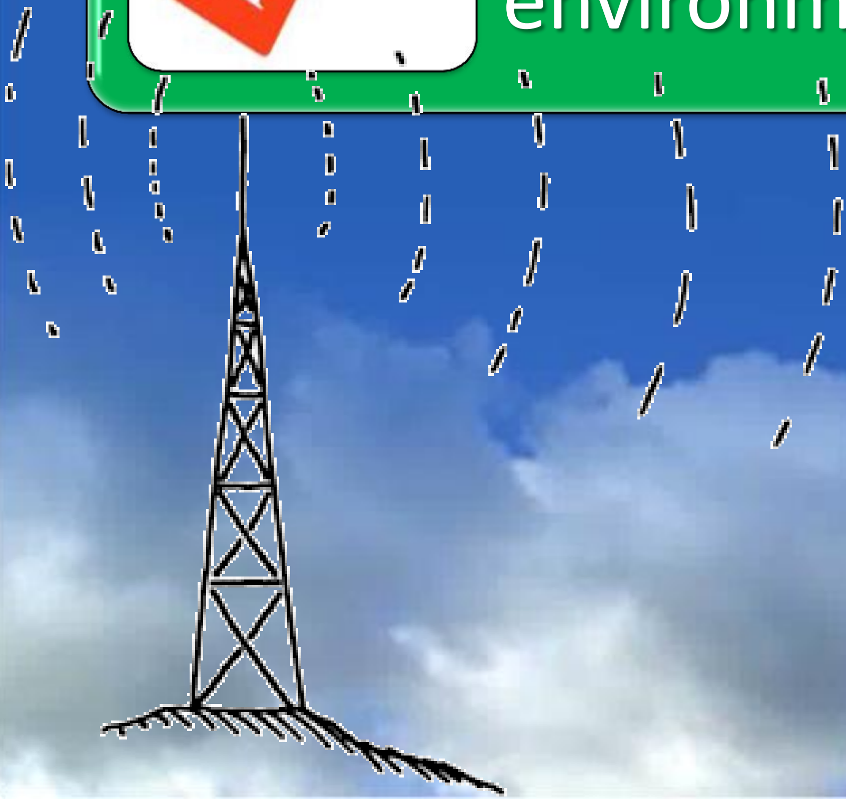
Environment *(Natural Resources, Recycled Products, Noise, Emissions…)*



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

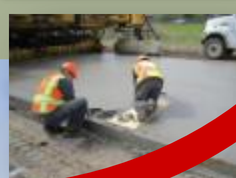
http://www.dot.ca.gov/newtech/roadway/pavement_lca/index.htm

Extraction
Production
Transport

Materials

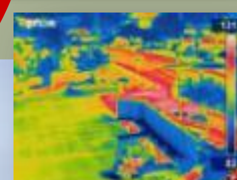
Traffic Delay
On-site Equipment

Construction



Rolling Resistance
Carbonation
Lighting
Albedo
Leachate

Use

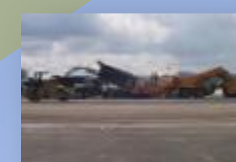


Traffic Delay
Extraction
Production
Transport

Maintenance, Preservation Rehabilitation

Traffic Delay
Salvage
Transport…

End-of-Life



CALIFORNIA DEPARTMENT OF
TRANSPORTATION

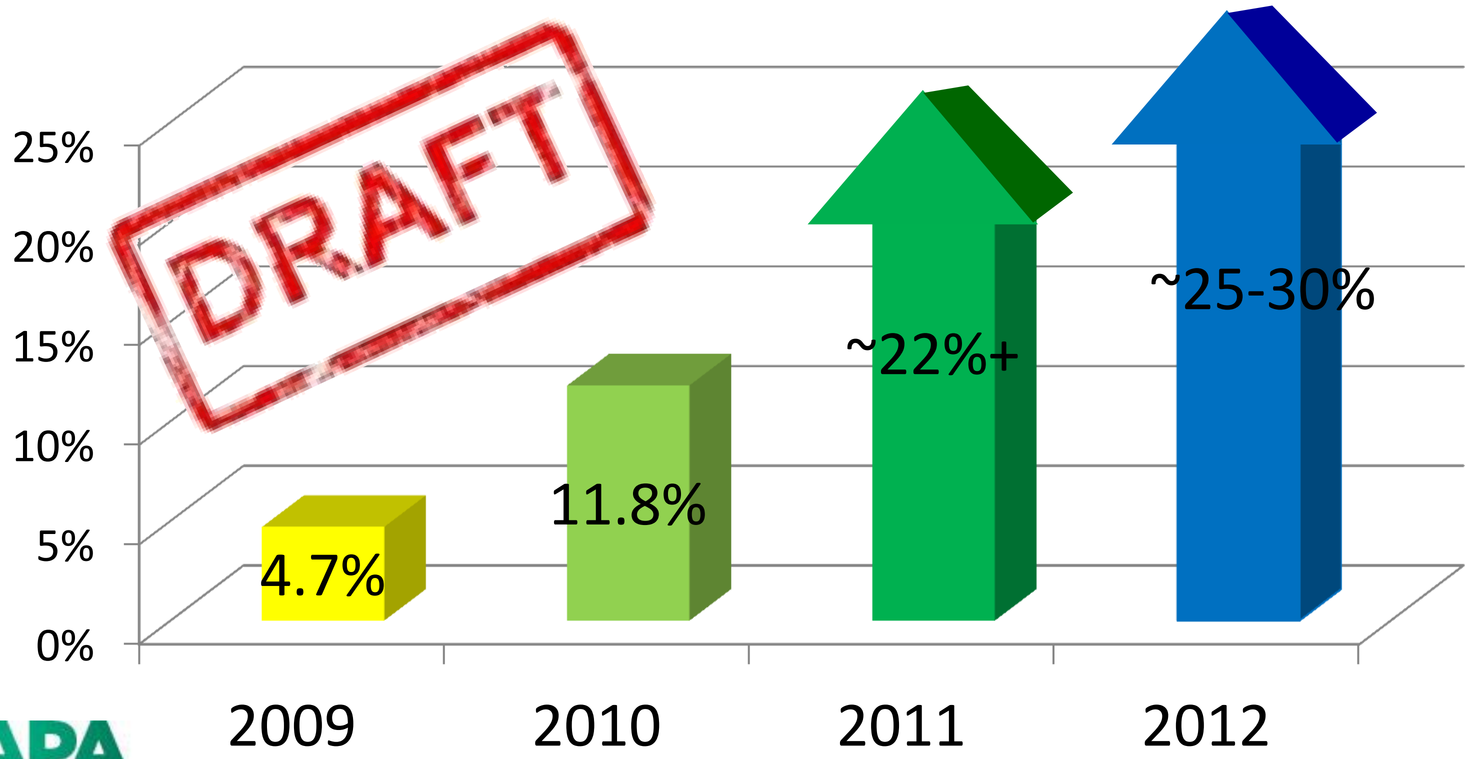
Ex. Estimate of Total US Emissions for Hot-Mix Asphalt Production

- 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 **HMA** Emissions ~
  - 8,222,000 US tons CO_2e

WMA Usage

Percentage of Total Asphalt Production in US

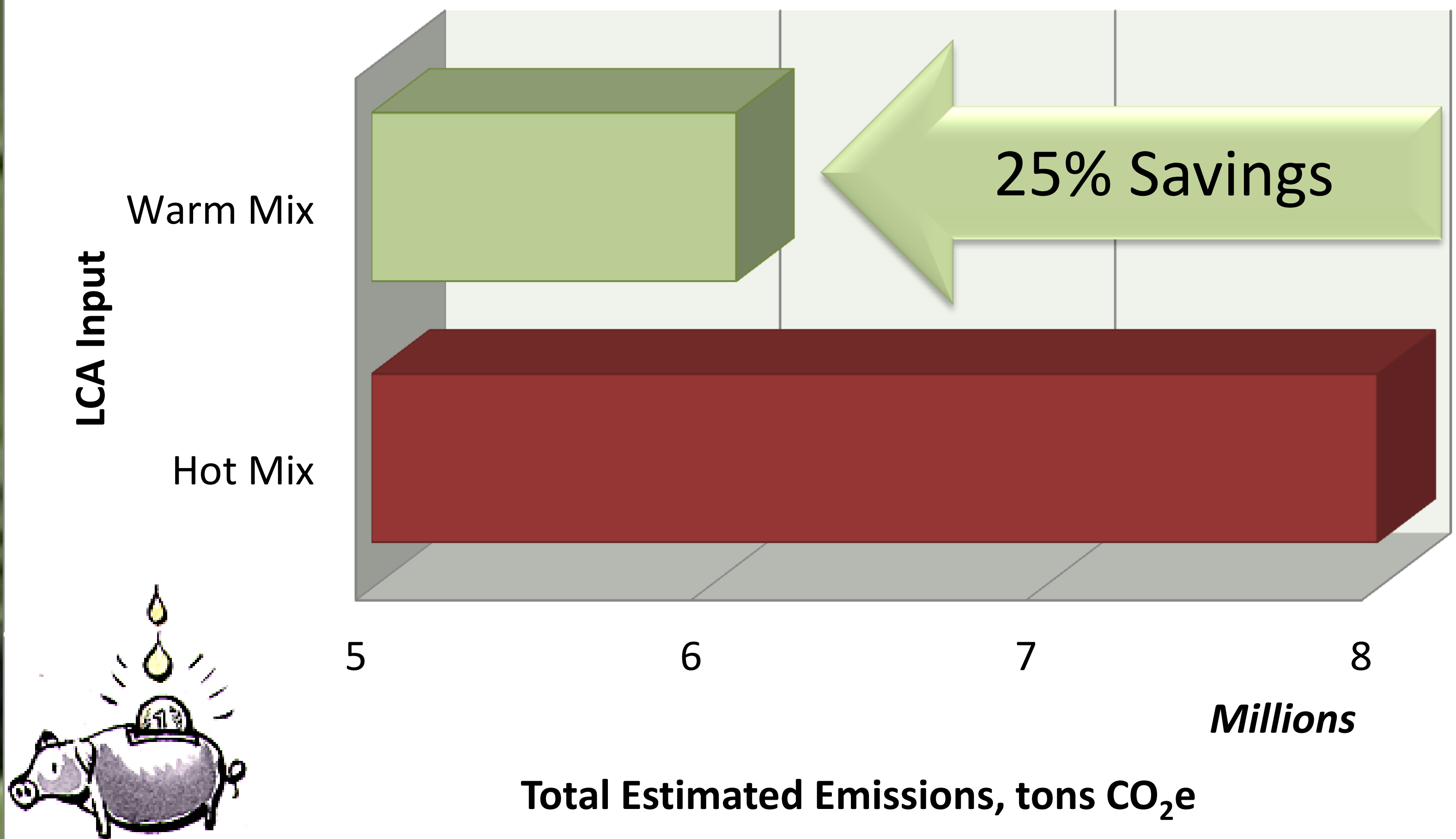
source: National Asphalt Pavement Association



NATIONAL ASPHALT PAVEMENT ASSOCIATION

As the US continues to move from Hot-Mix to WMA WARM-MIX ASPHALT

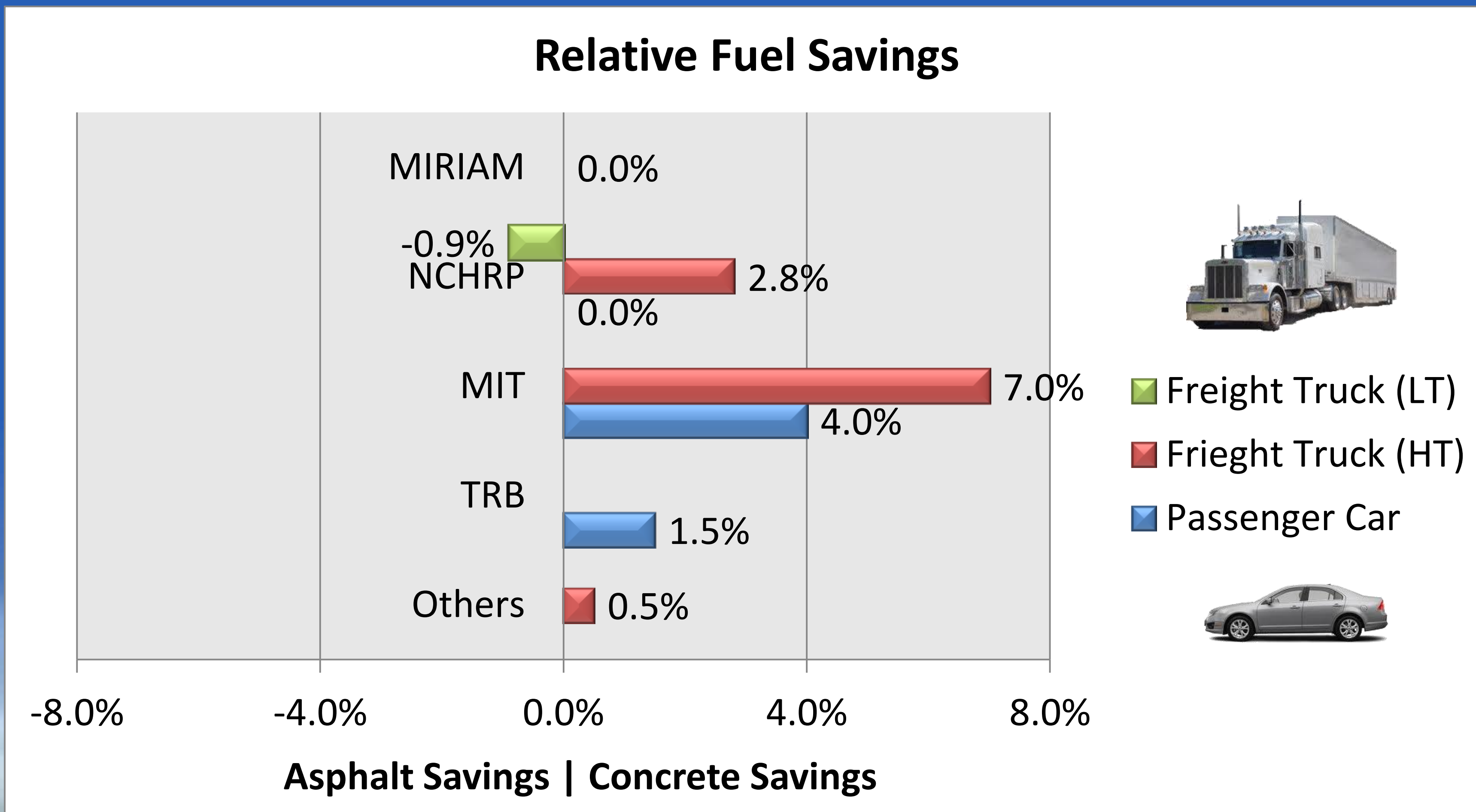
Equivalent of removing 1.5 million cars of the road each year!



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

Recent Focus

Various Thoughts on Use Phase

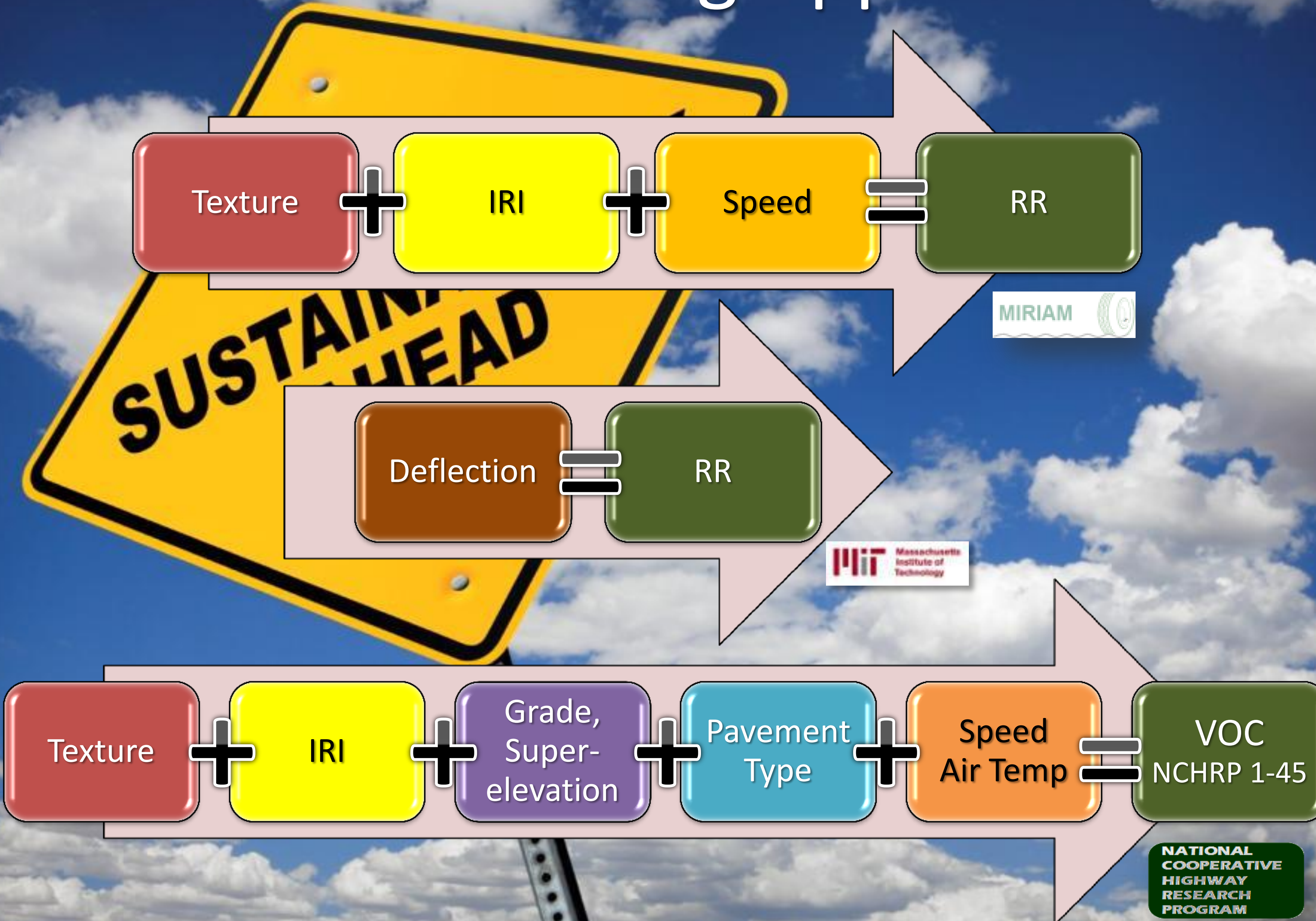


How is this information being used?

Proving the Adage

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

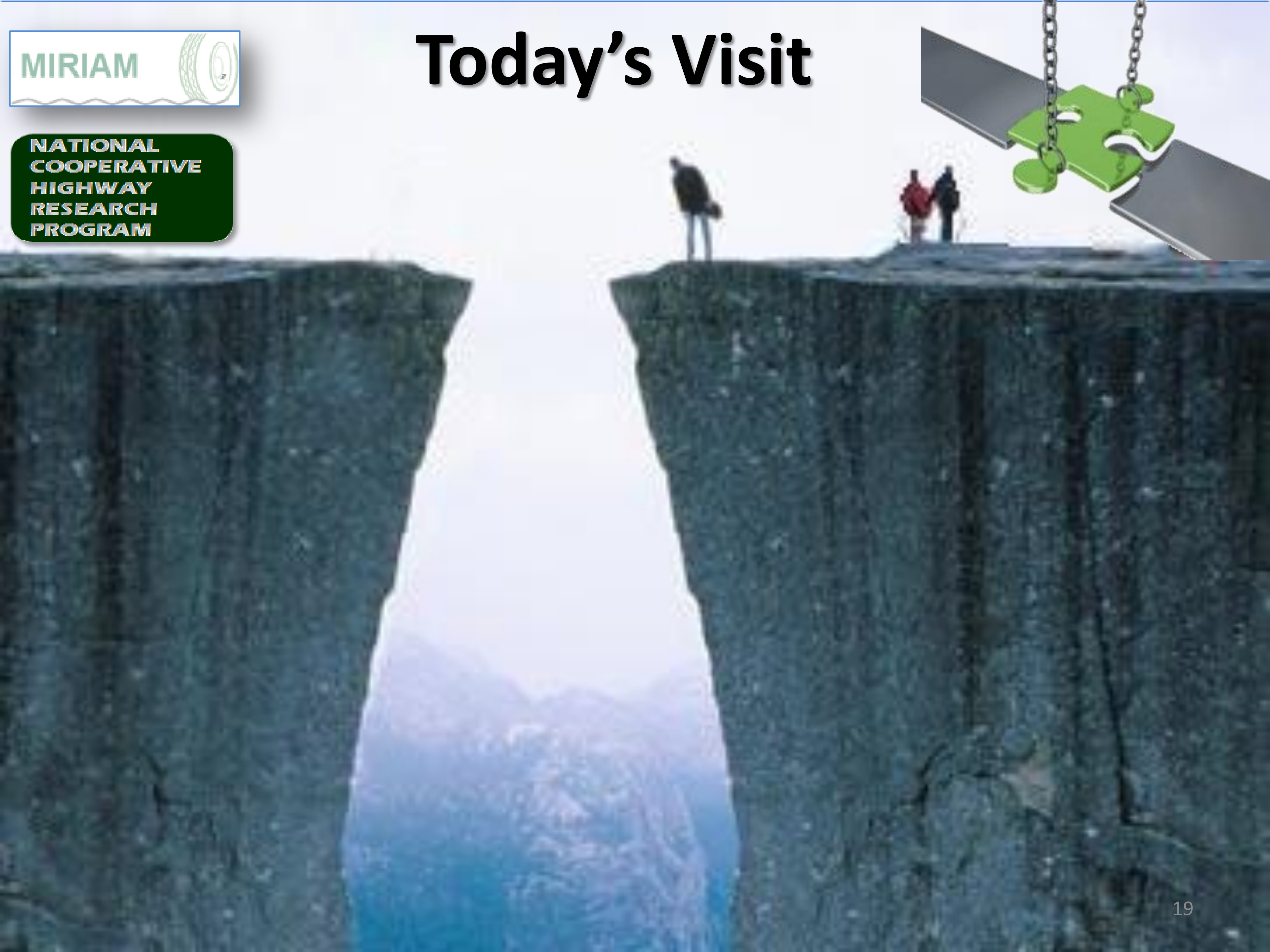
Various Modeling Approaches



Today's Visit

MIRIAM

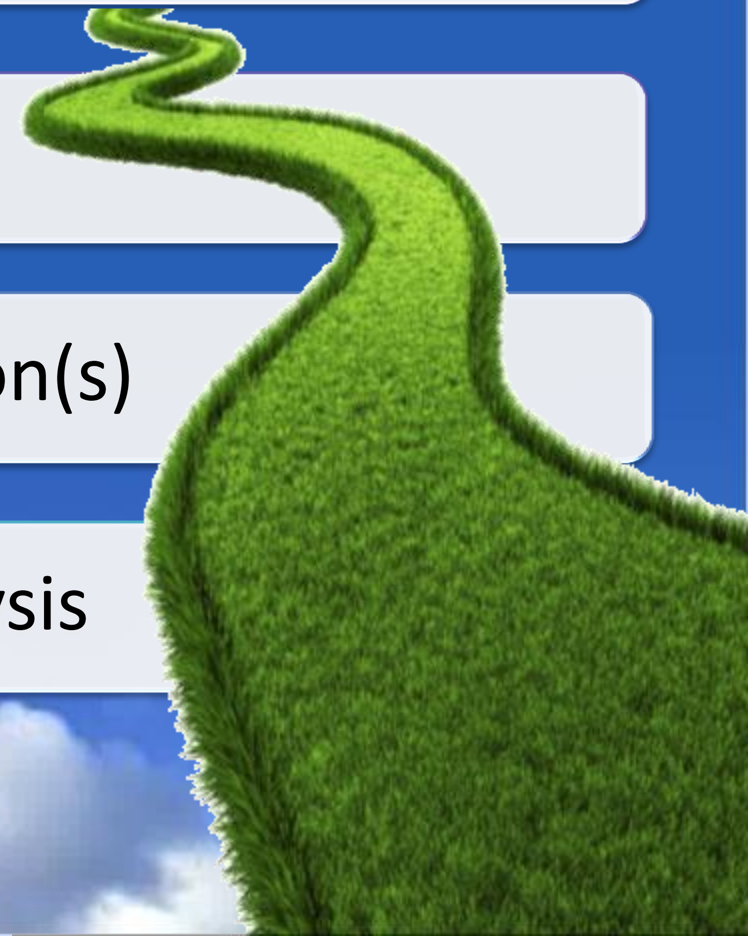
NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM



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)?

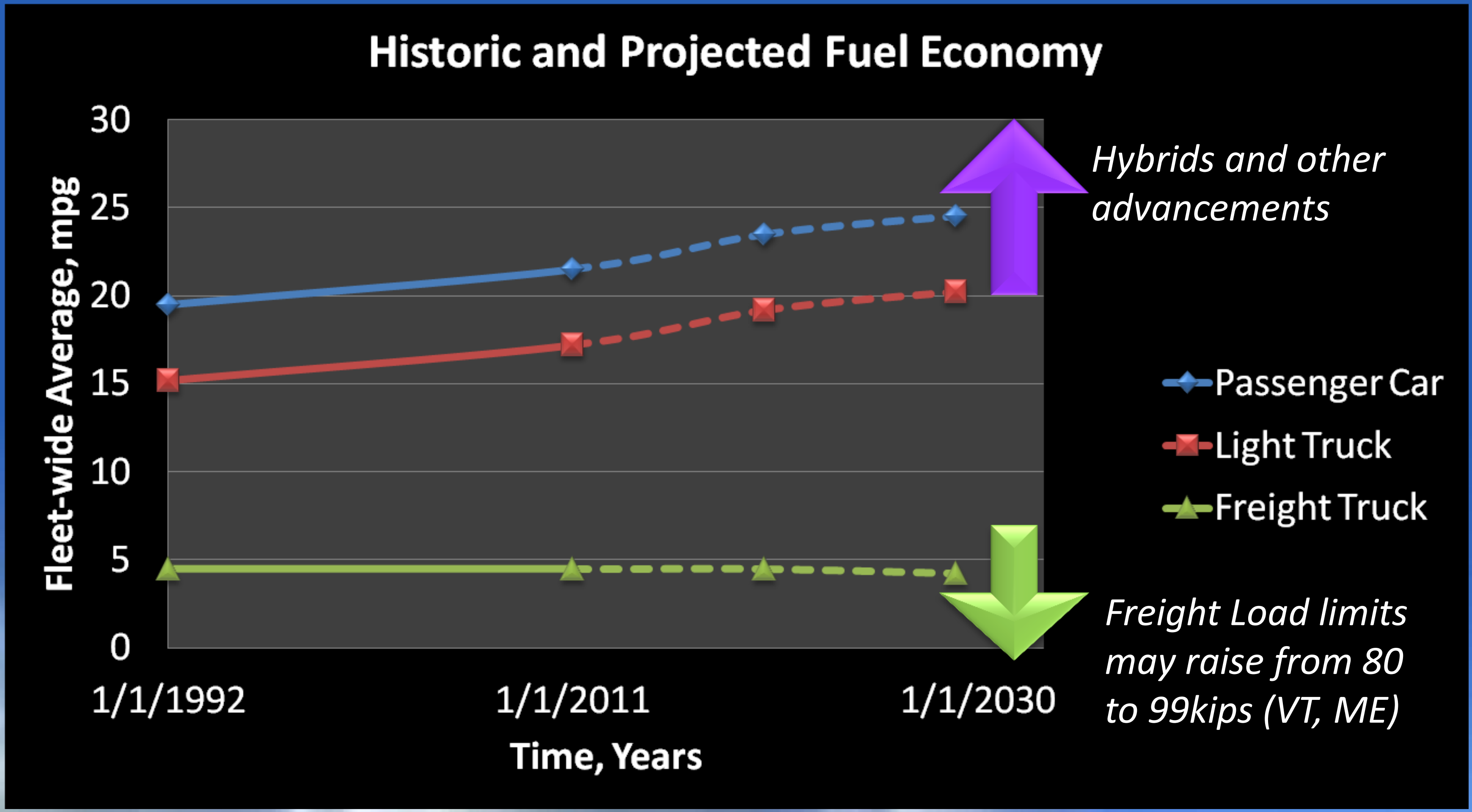
A. 18.5 mpg
B. 21.5 mpg
C. 23.0 mpg
D. 25.5 mpg

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

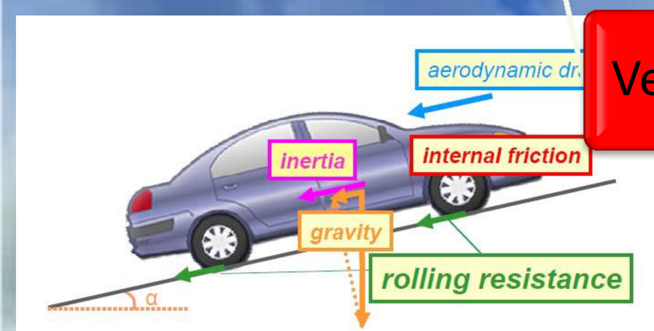
Bjarne Schmidt, Danish Road Directorate, Denmark

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

} 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

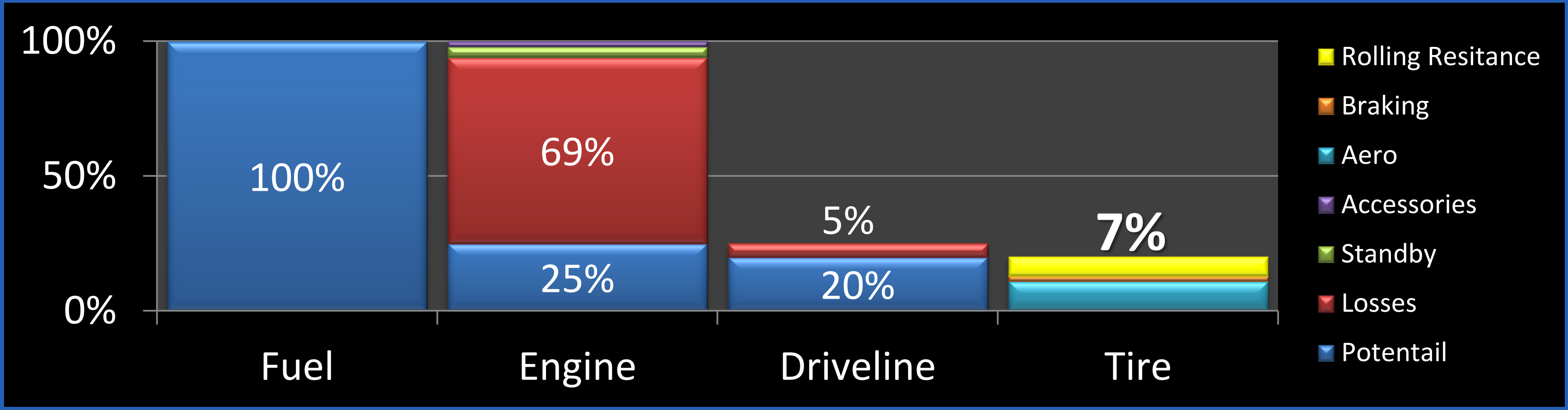
  ~25% of fuel consumption is used to overcome RR

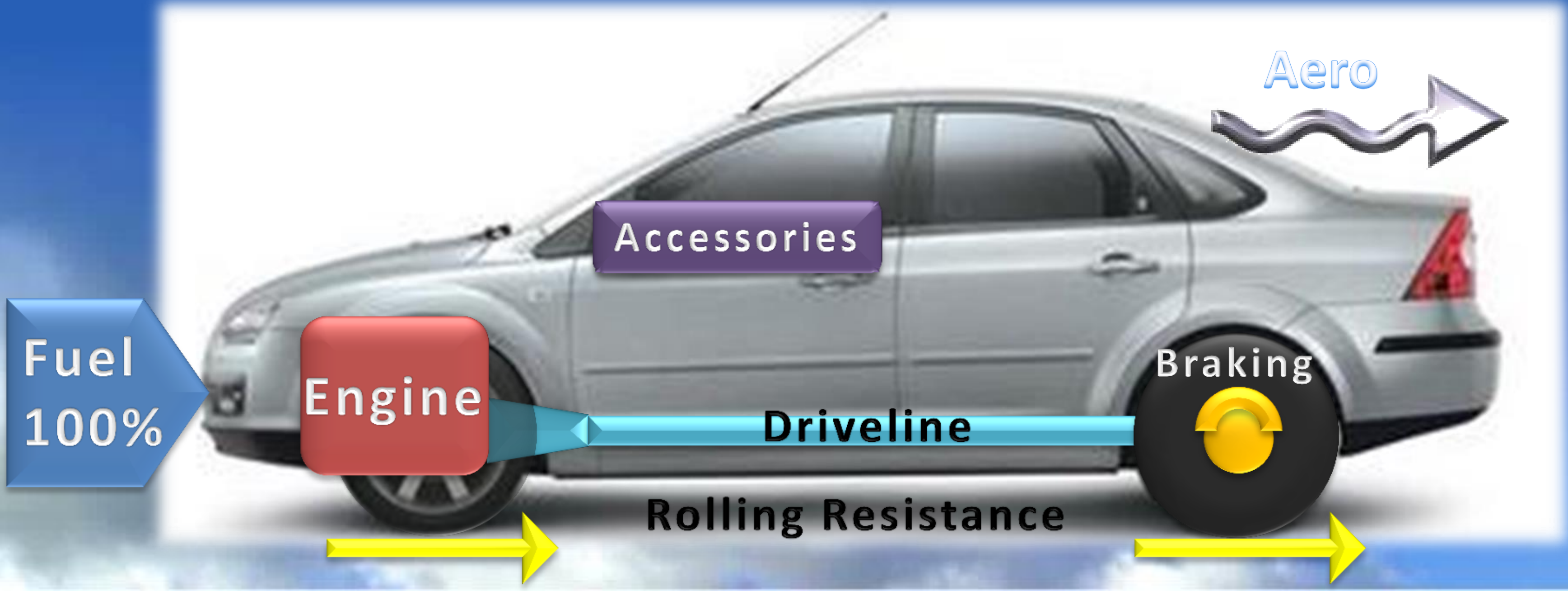
Tire Wear, Traction, & Force Generation
Automotive View on Rolling Resistance

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

Alternatively: Highway Driving

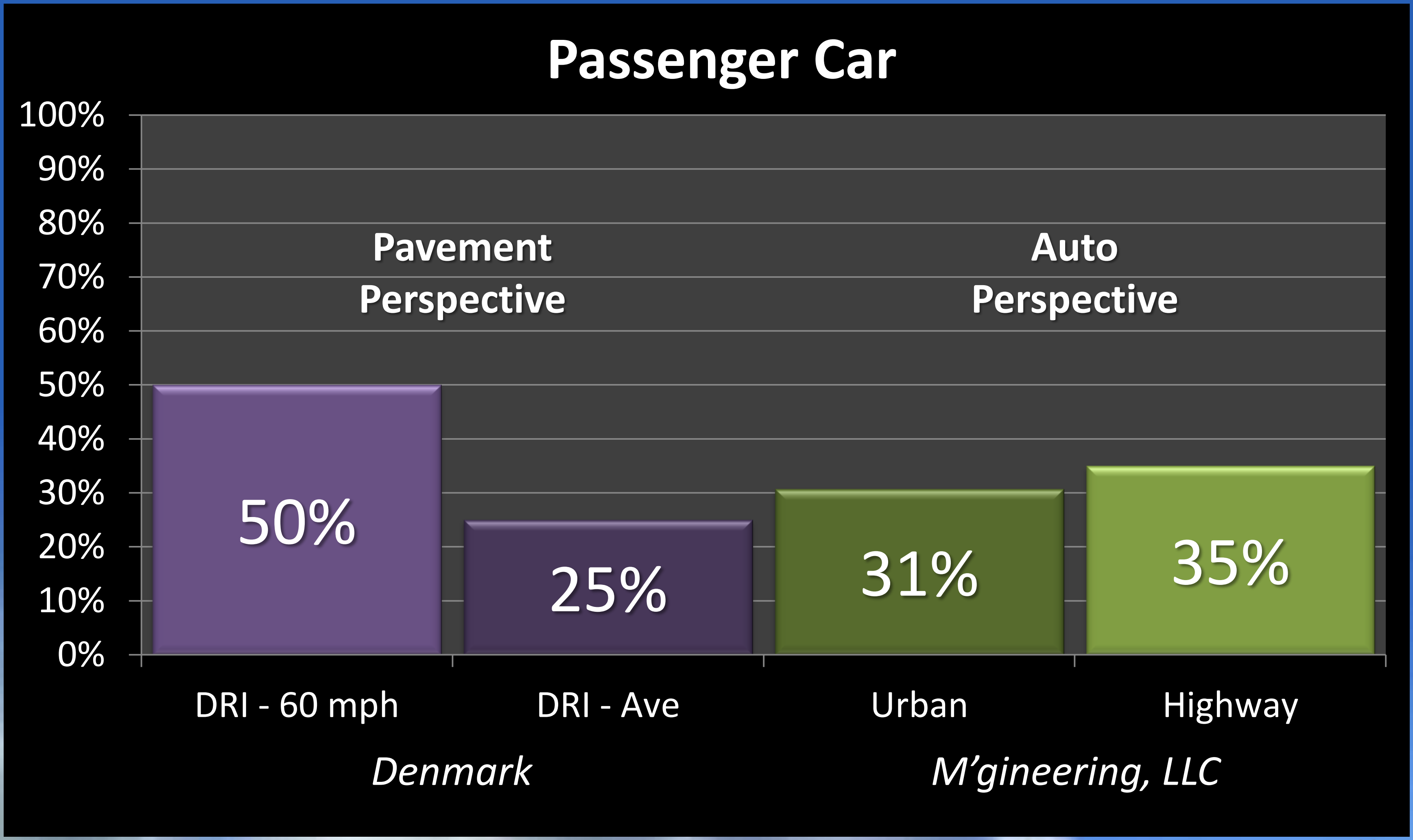
(Source: M'gineering, LLC: Dr. Mariom Pottinger)





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)

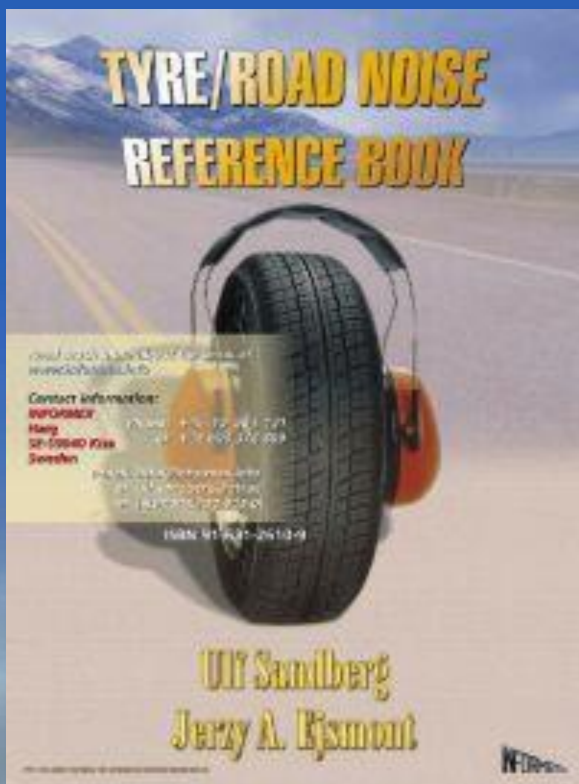
No
- Temperature, *f*(nature)

Yes
- Smoothness, *f*(time)


Texture

Understanding Tire/Pavement Interaction

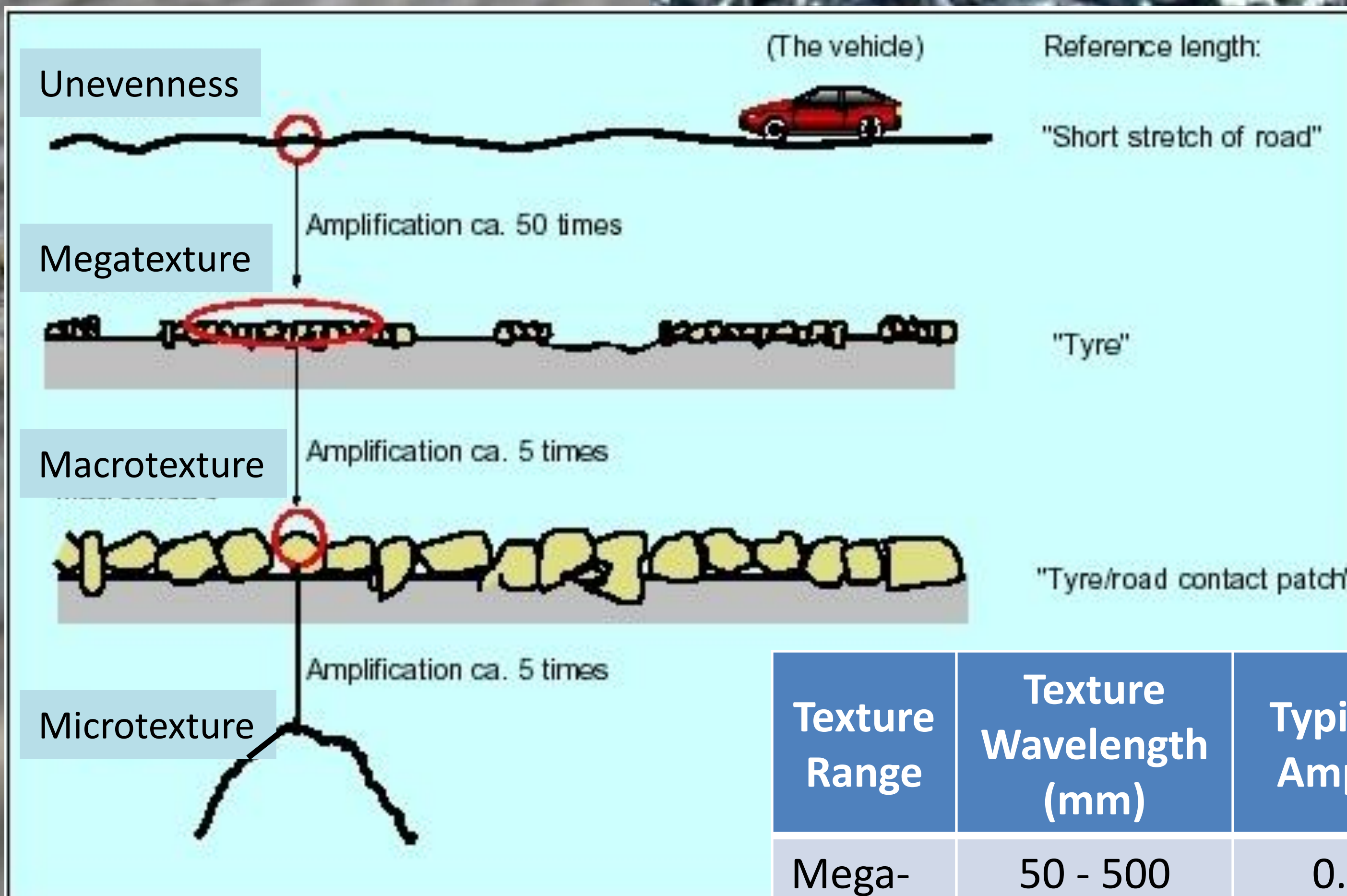
- Key Reference:
  - Tyre/Road Noise Reference Book



Ulf Sandberg

Jerzy A. Ejsmont

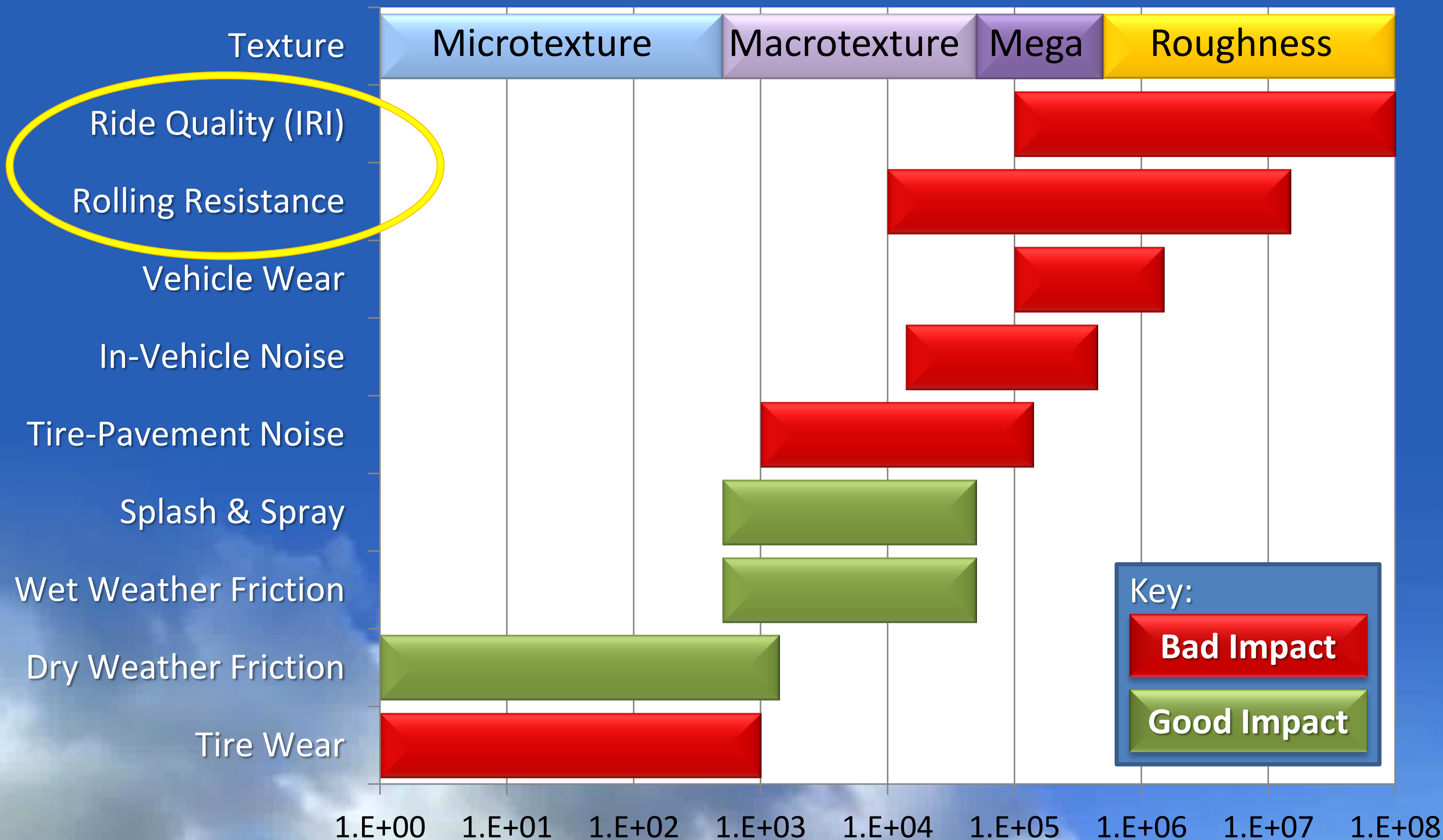
Pavement Texture Ranges
Defined by Sandberg, et.al.



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

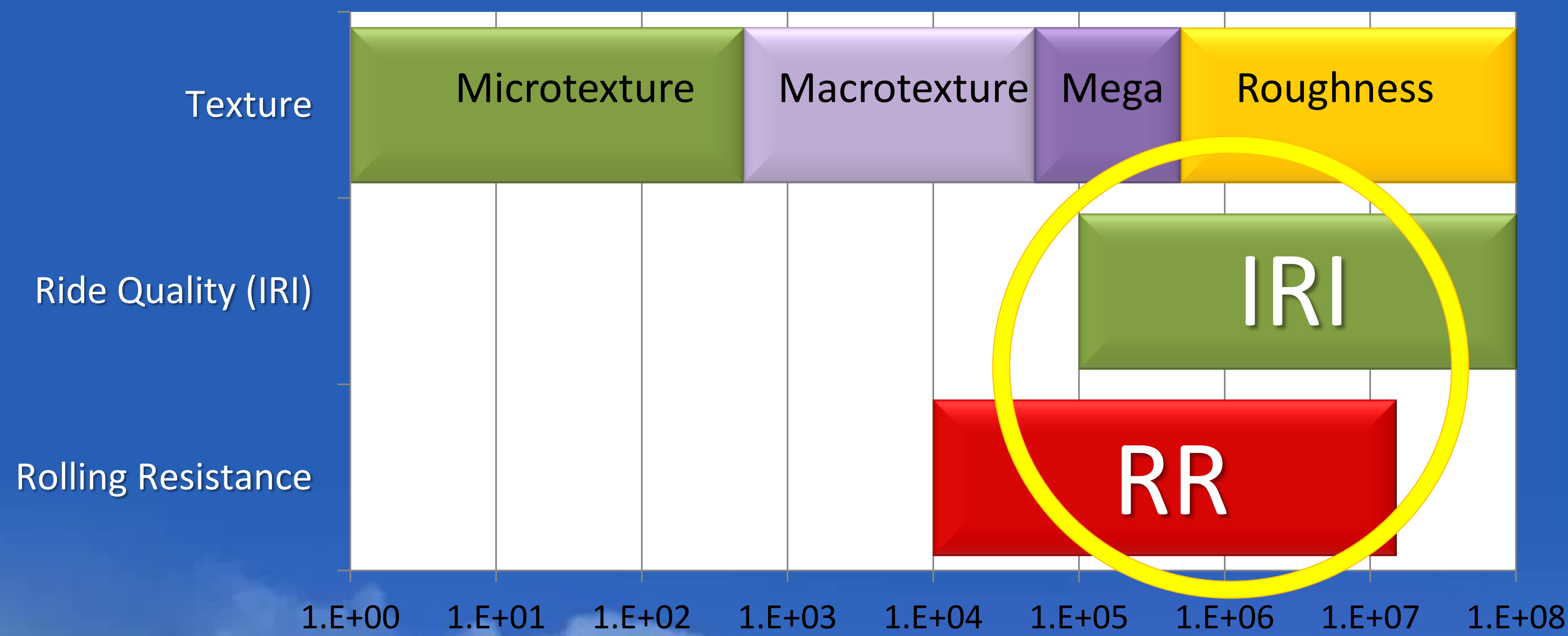
PIARC Pavement Surface Characterizes

(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 3*d*.

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

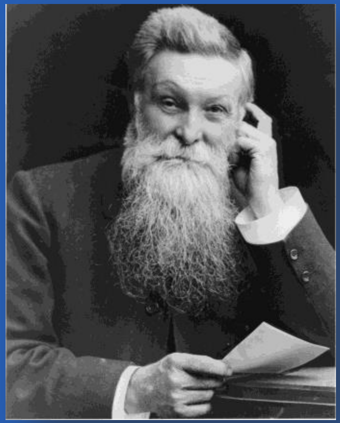
THOMSON'S PATENT AERIAL WHEELS.

Fig. 1.

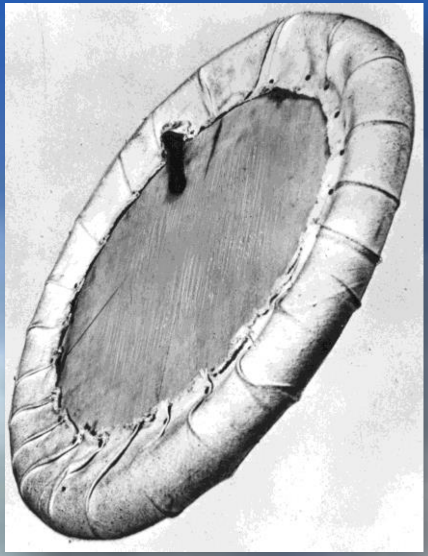
Result of Experiments tried by Messrs. Whitehurst and Co., and the Patentee, for ascertaining the comparative Draught of R. W. Thomson's Patent Aerial Wheels and the common Wheels. Tried in Regent's Park, March 17, 1847.

Weight of Carriage, 10½ 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	38½	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

US RR Device?

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

- Automotive perspective.

MIRIAM Modeling Rolling Resistance

Texture + IRI + Speed = RR

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

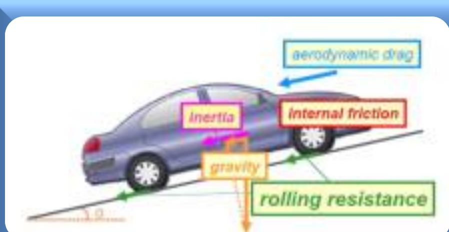
Where:

- 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

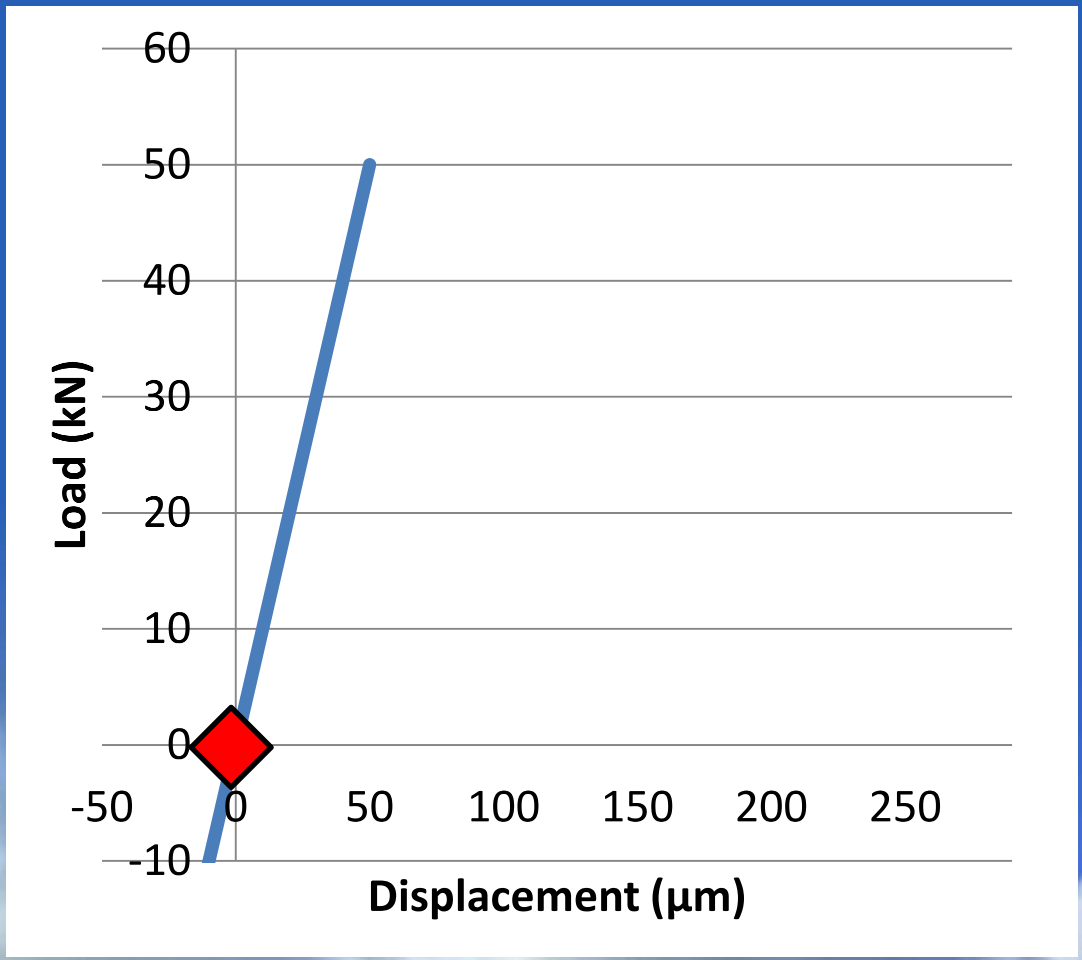


10:3

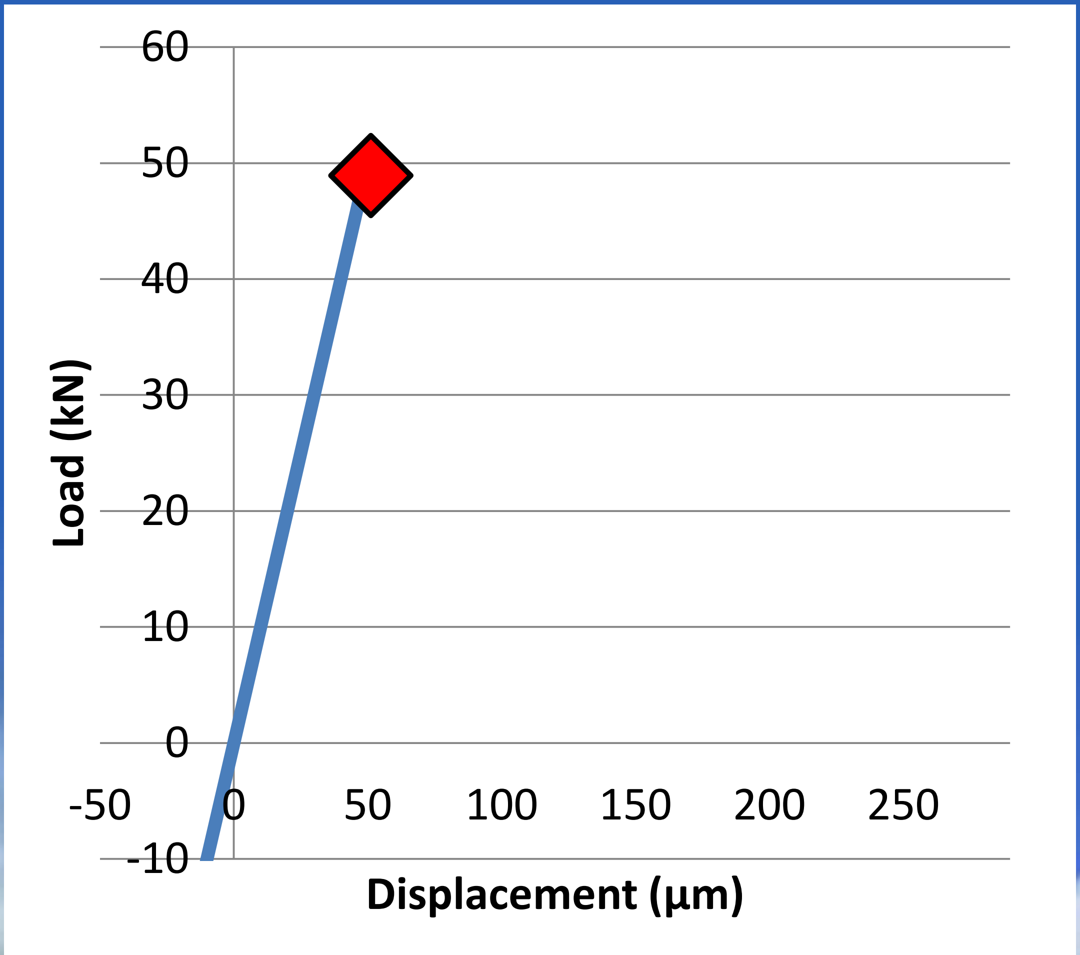
Road Directorate

Stiffness

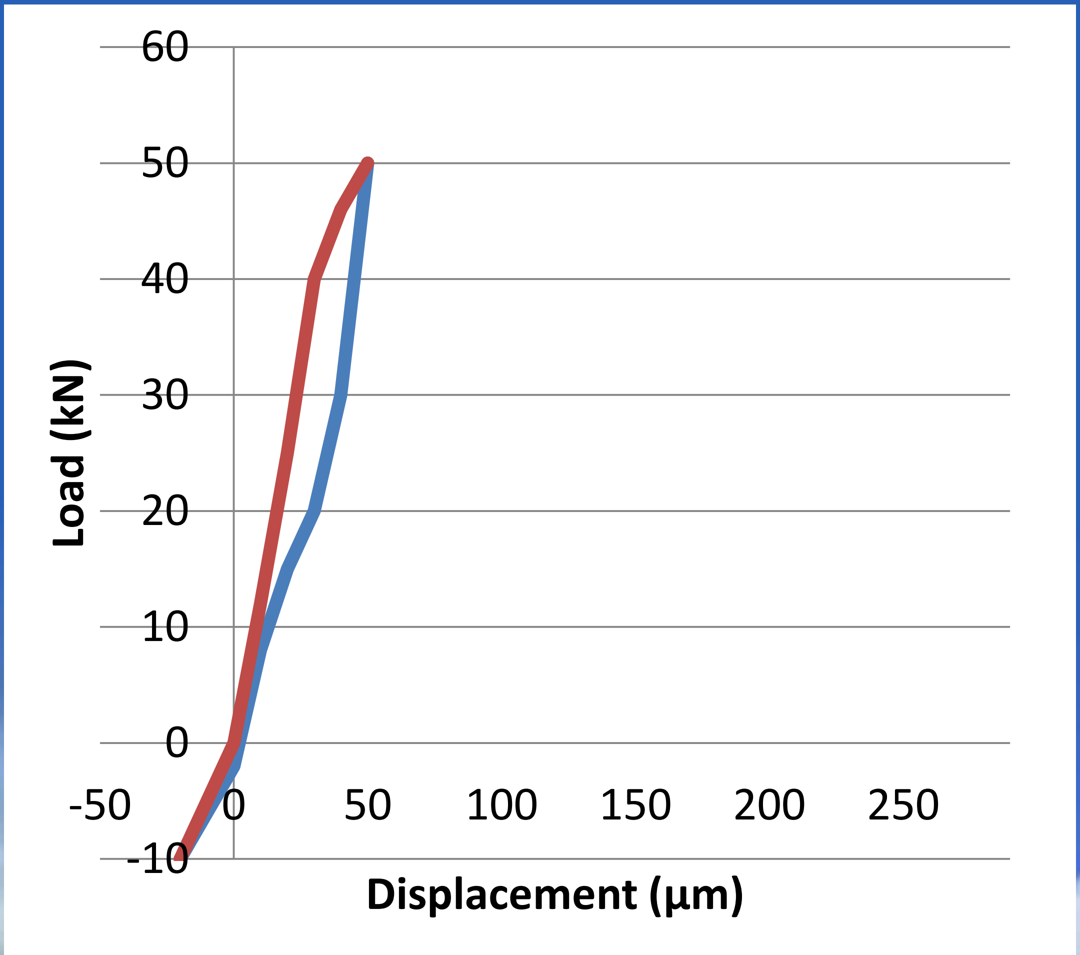
Stiffness Concept
Ideal Spring: load/unload *(no losses)*

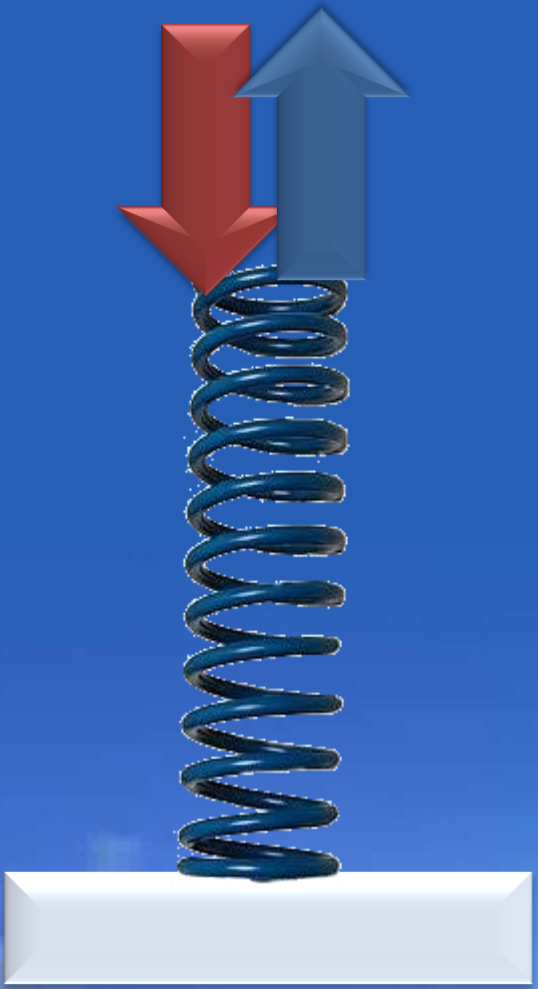


Stiffness Concept
Ideal Spring: load/unload

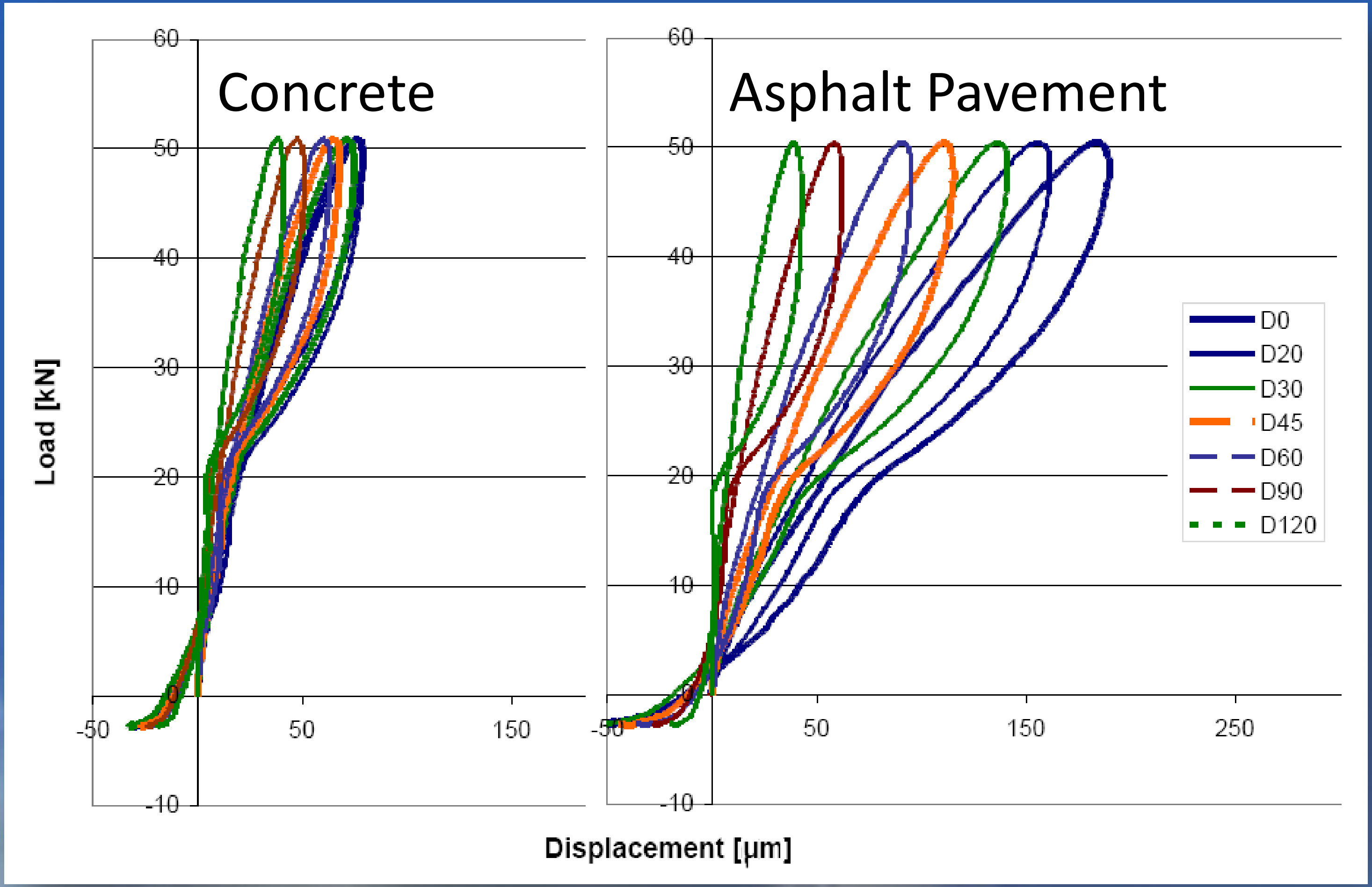


Hysteresis effect
Energy Loss during load/unload





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

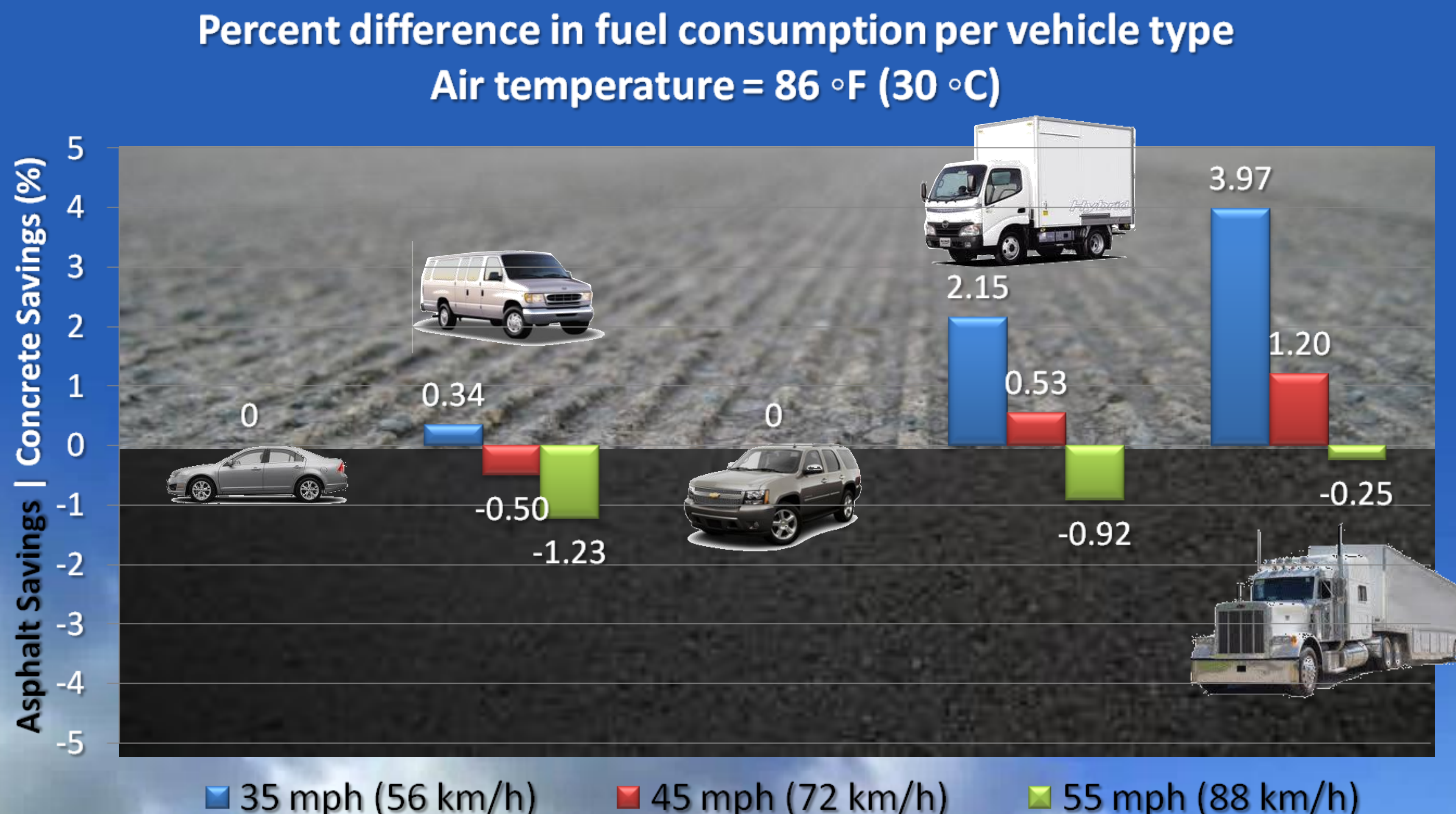


Hysteresis effect measured with a Falling Weight Deflectometer (FWD) on a concrete pavement (left), compared to an asphalt pavement (right)

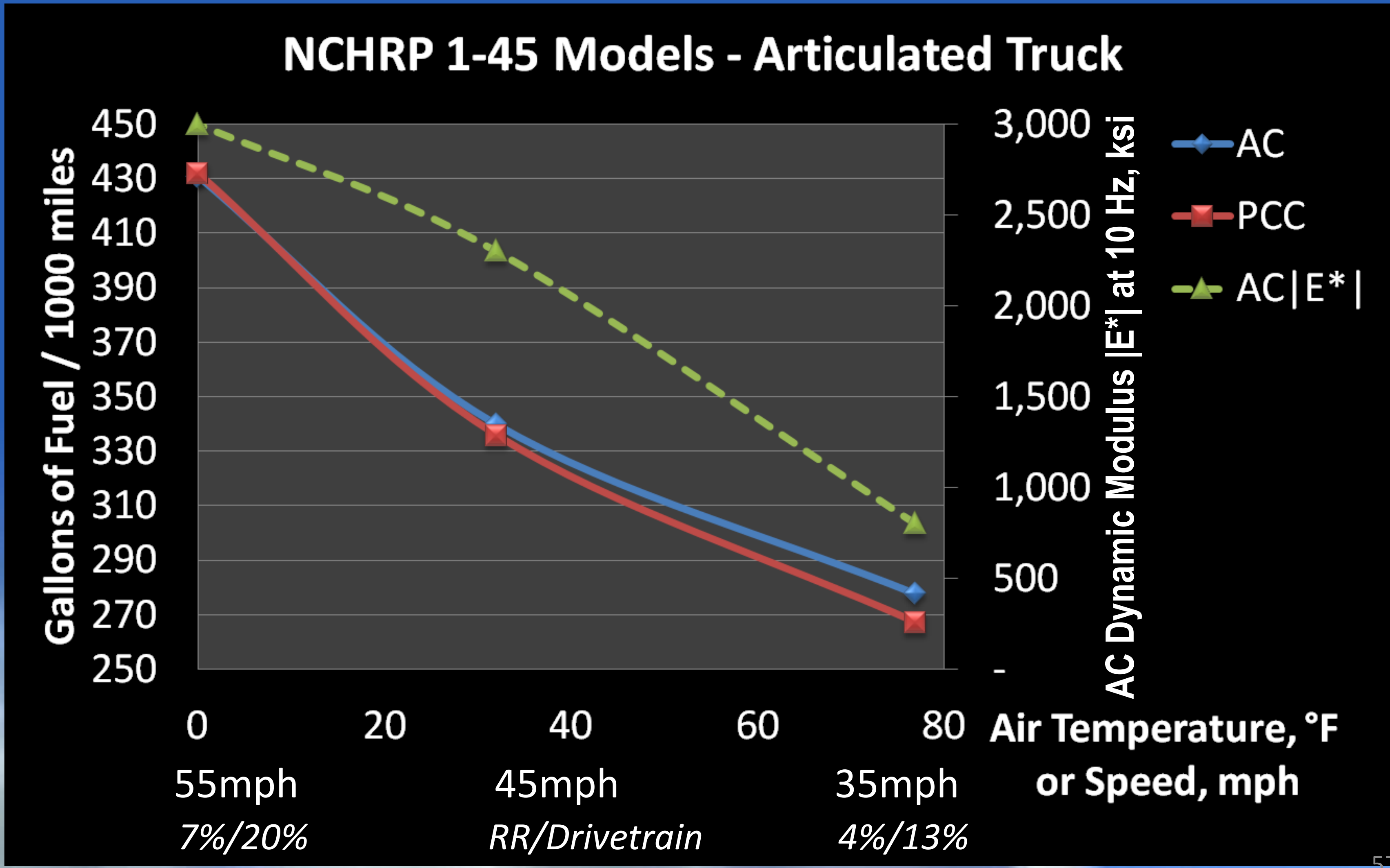
However… NCHRP 1-45 VOC Model

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

IRI = 95 in/mile, MPD = 0.05 in, 80°F



1-45 Model Fuel Consumption for Asphalt & Concrete




Smoothness

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**

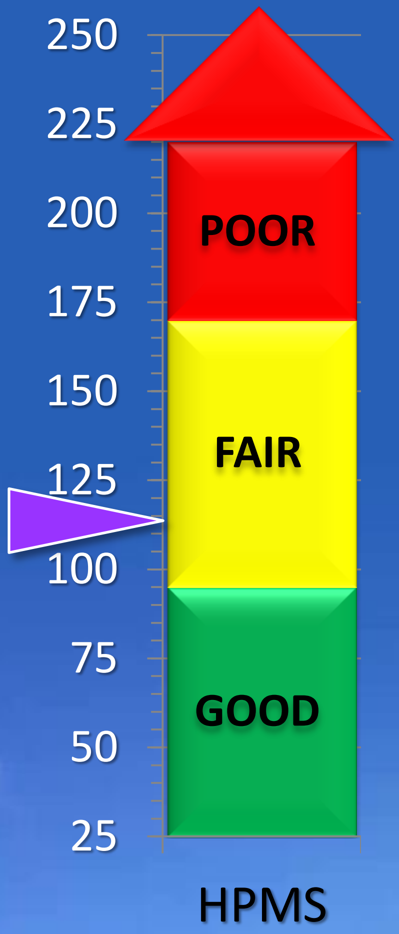
ACPA

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

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

- Simplified IRI Model for Superpave (Interstate)

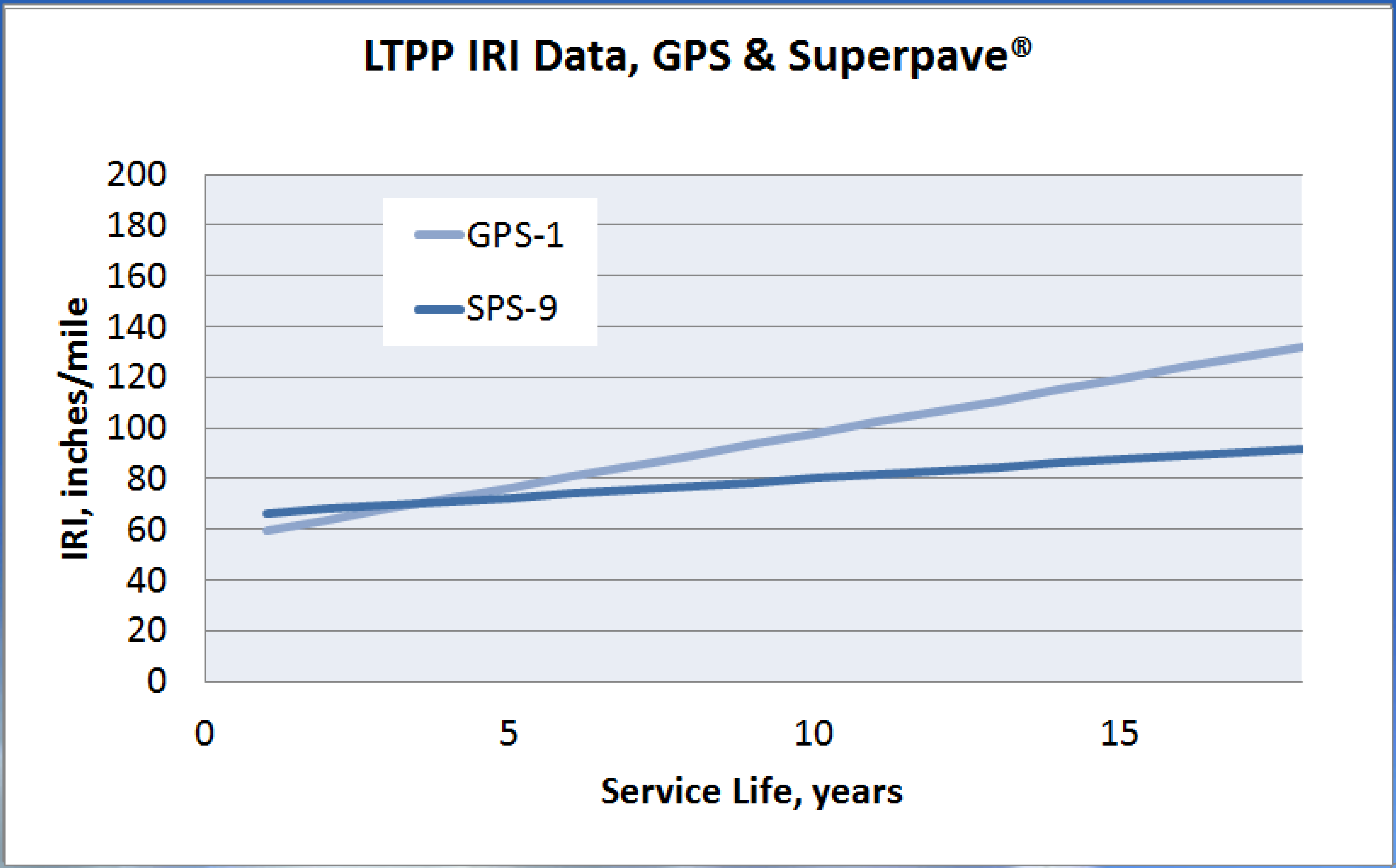
$IRI_t = IRI_0 + 1.4$ Time (yr), *in/mile*

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

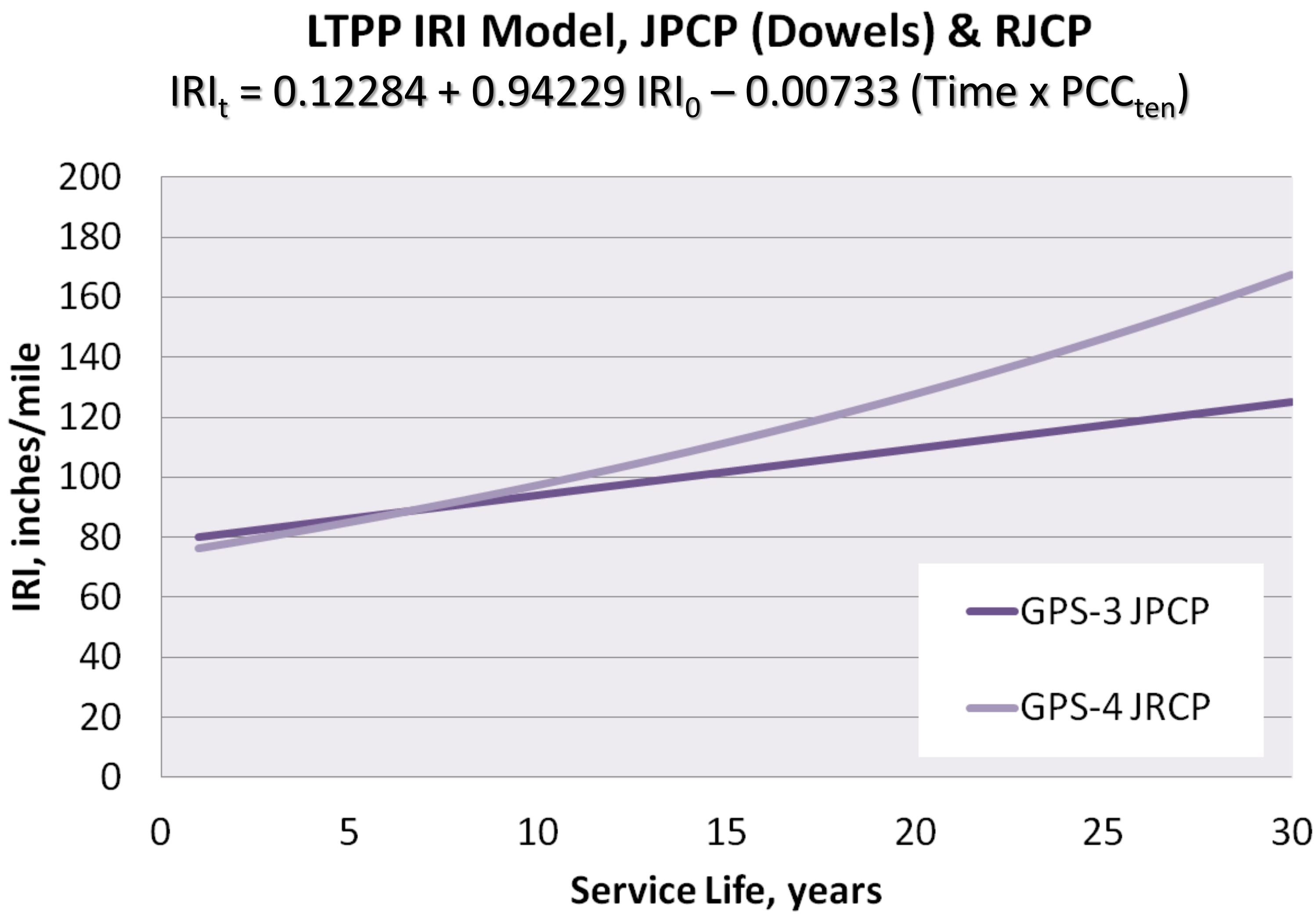
$IRI_t = 85 + 1.8\ t$ *(Scenario), overlay @ 18+*

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)

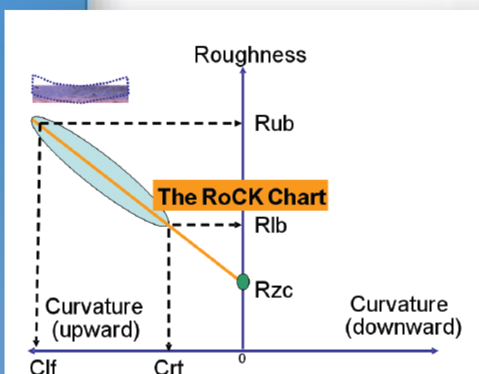


Not Considered… Yet

TechBrief

JULY 2010 | FHWA-HIF-10-010

Our understanding of concrete pavement roughness has advanced considerably…



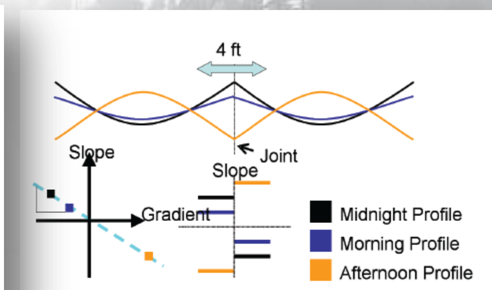


FIGURE 6. Joint functionality analysis showing diurnal effects.

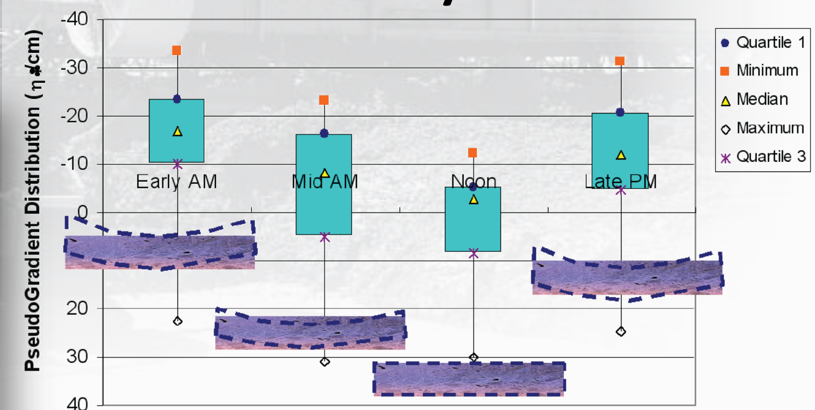


FIGURE 4. Diurnal curvature analysis. Example of a box plot for a test section where most of the slabs are curled up.

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

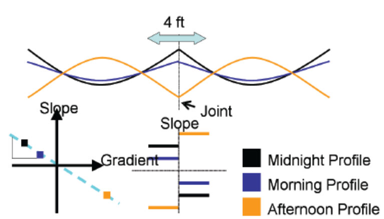


FIGURE 6. Joint functionality analysis showing diurnal effects.


What about
Texture?

Data Gaps

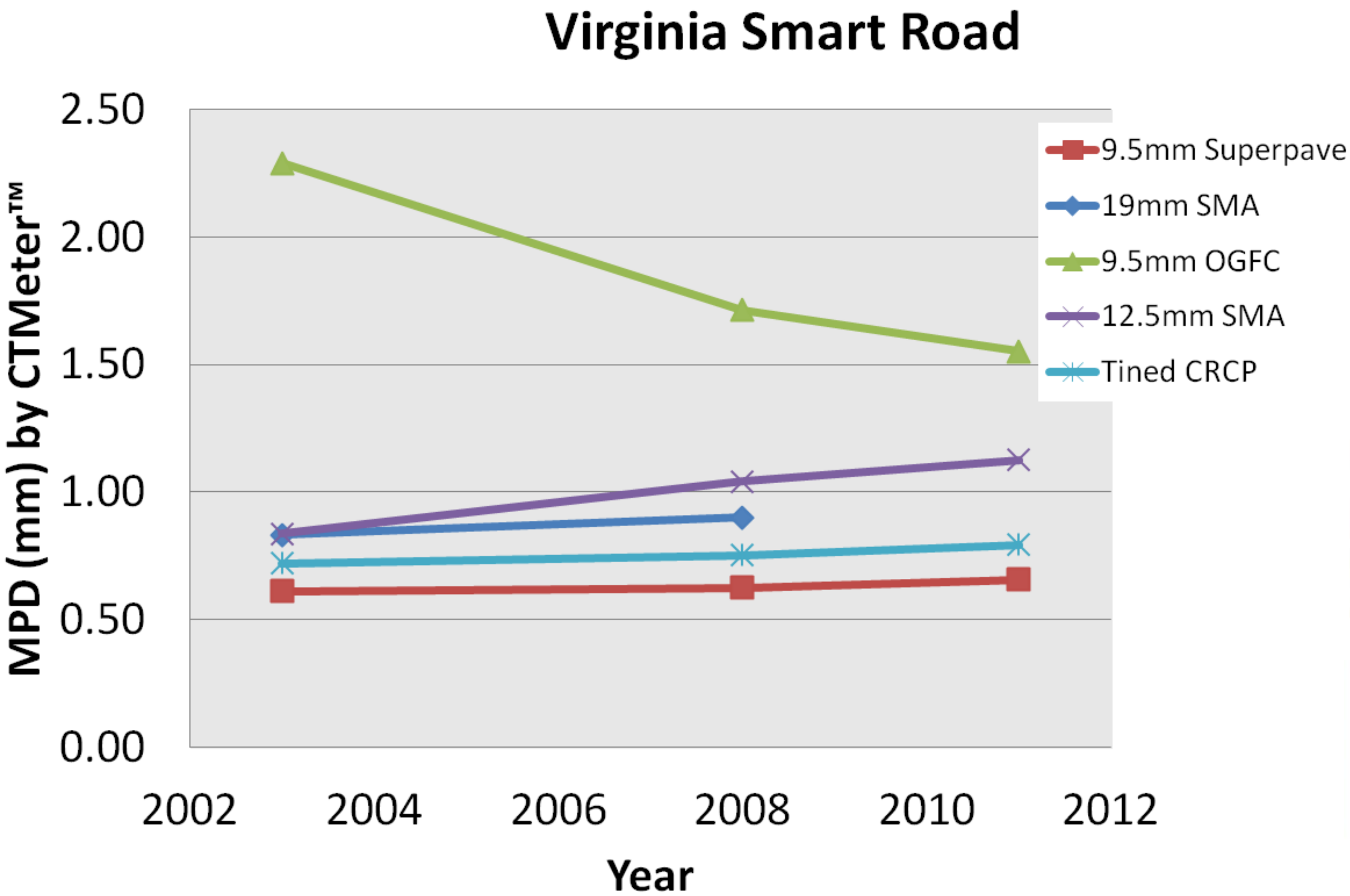
- Megatexture Texture Data:
  - US currently does not collect texture on a project or network level on roadways

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

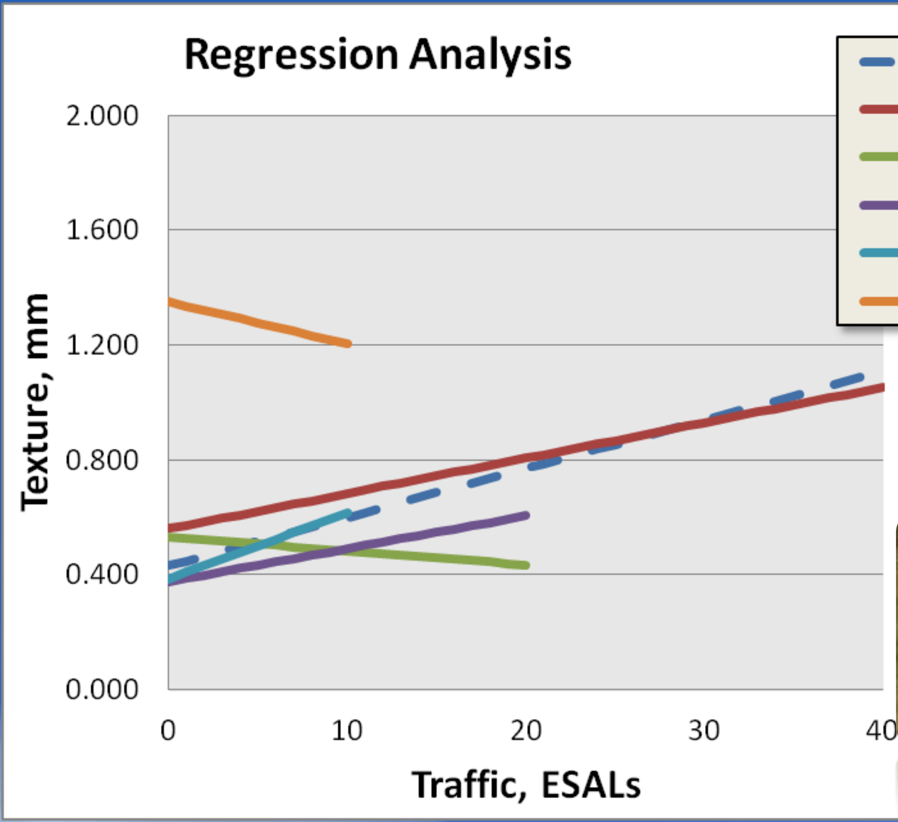
2009 CT DOT
LTPP SPS 9 Sections,
Constructed in 1998 (t = 11 years)

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

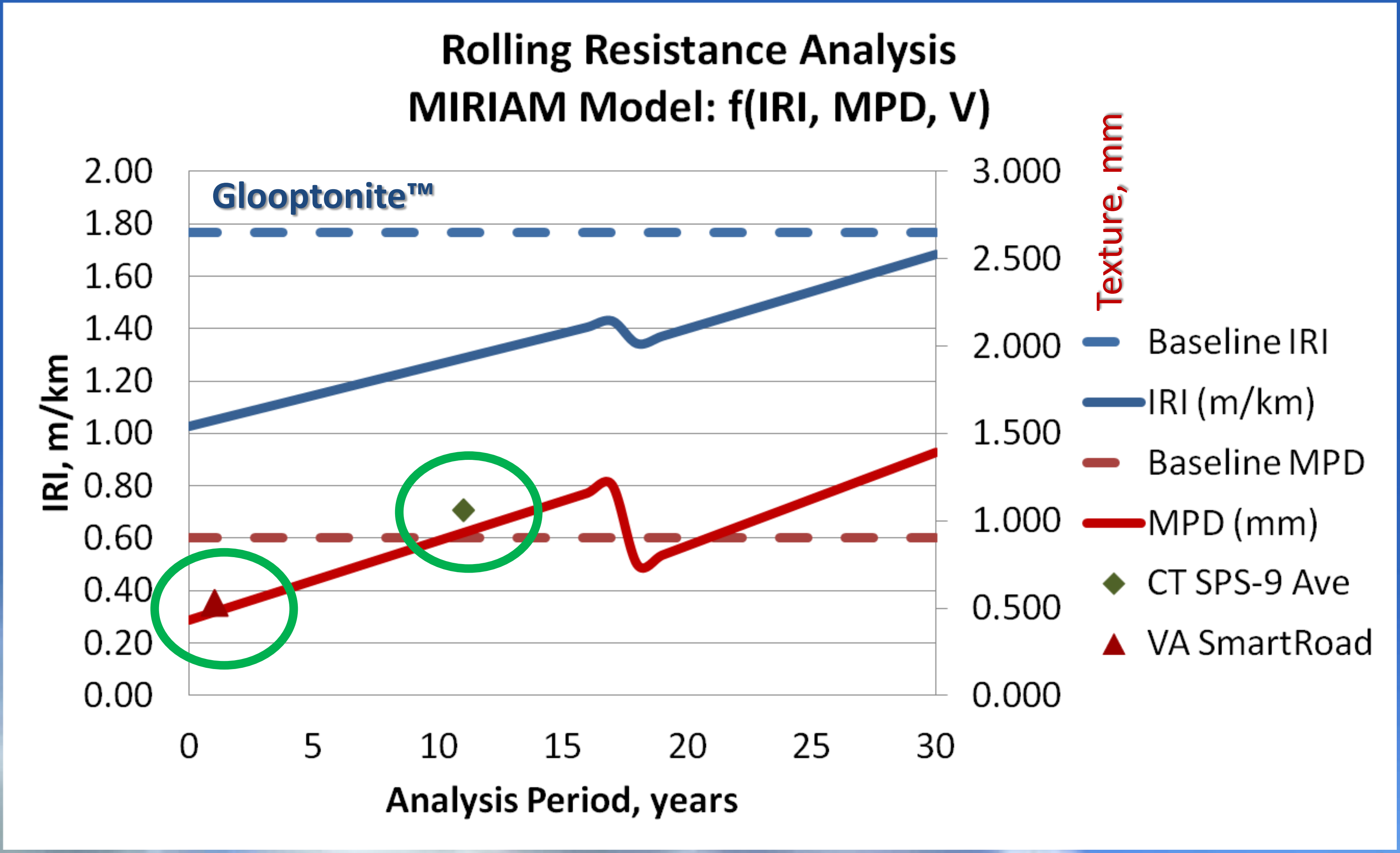
Test Track 2003 to 2010 Superpave Mixes

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



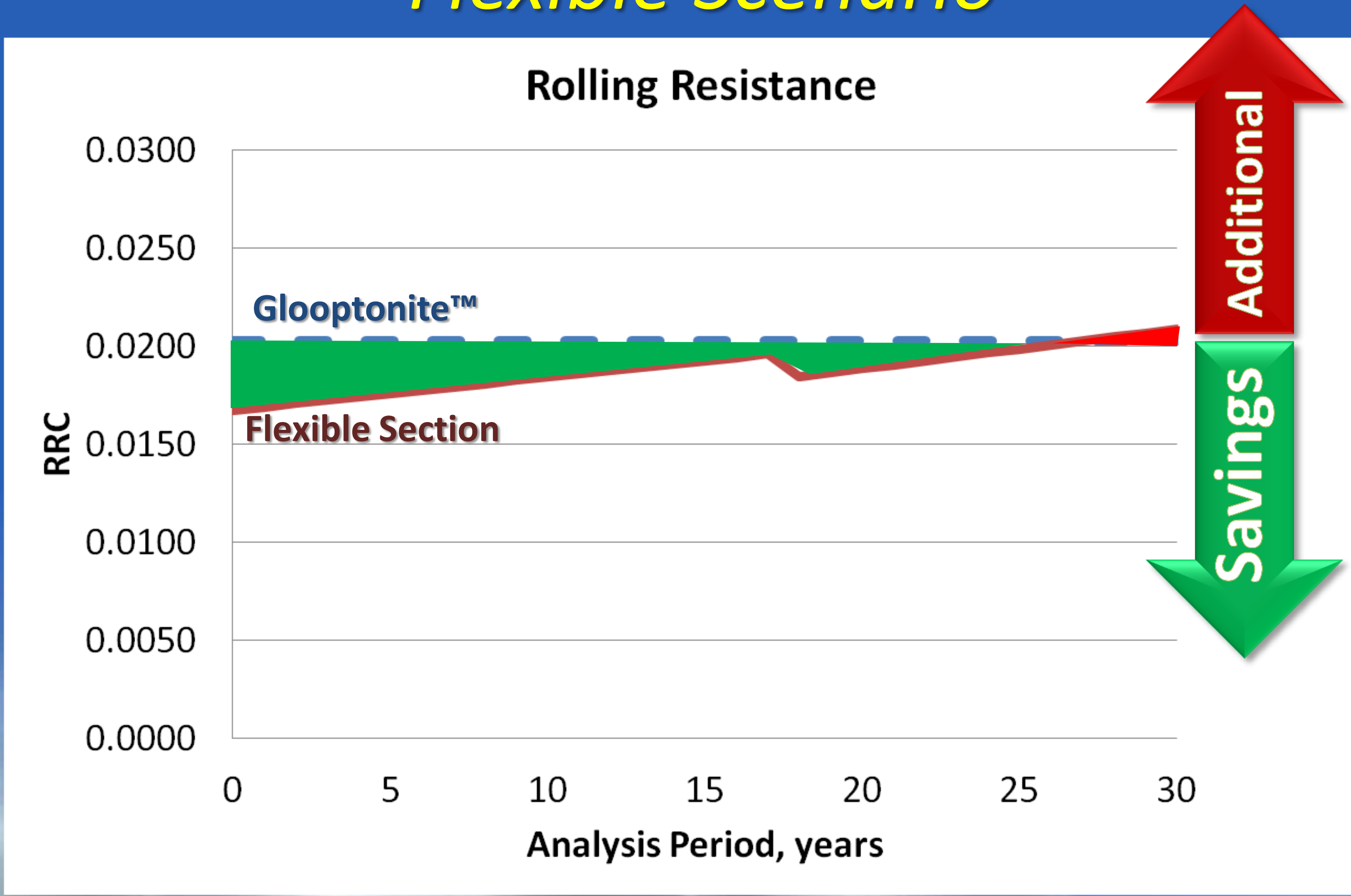
- Ave. Initial Texture (mm) = 0.431
- Ave. Change (δMPD / δmESALs) = 0.017, ranging from -0.015 to 0.023
- Average R^2 = 0.70

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



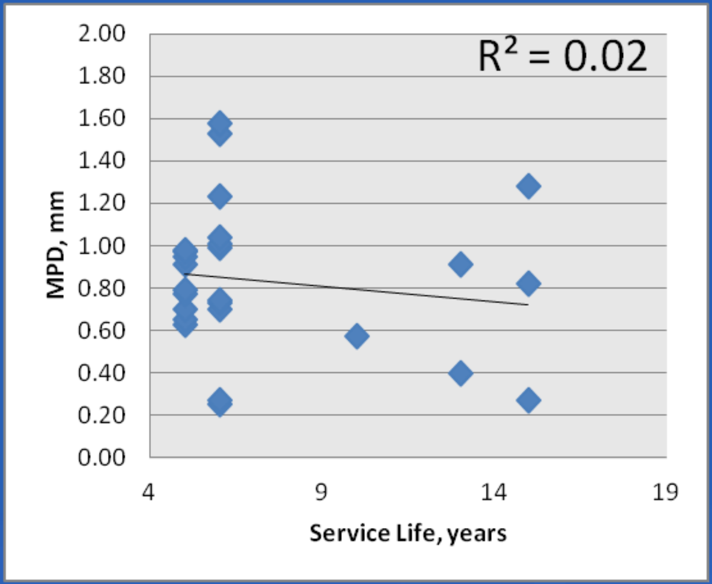
MIRIAM RRC *f*(IRI, MPD)

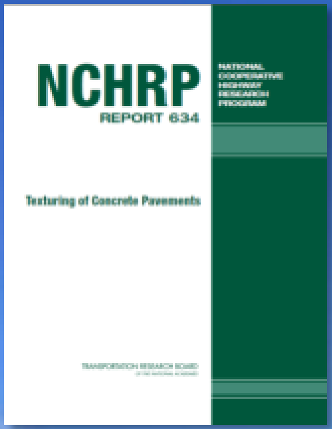
Flexible Scenario



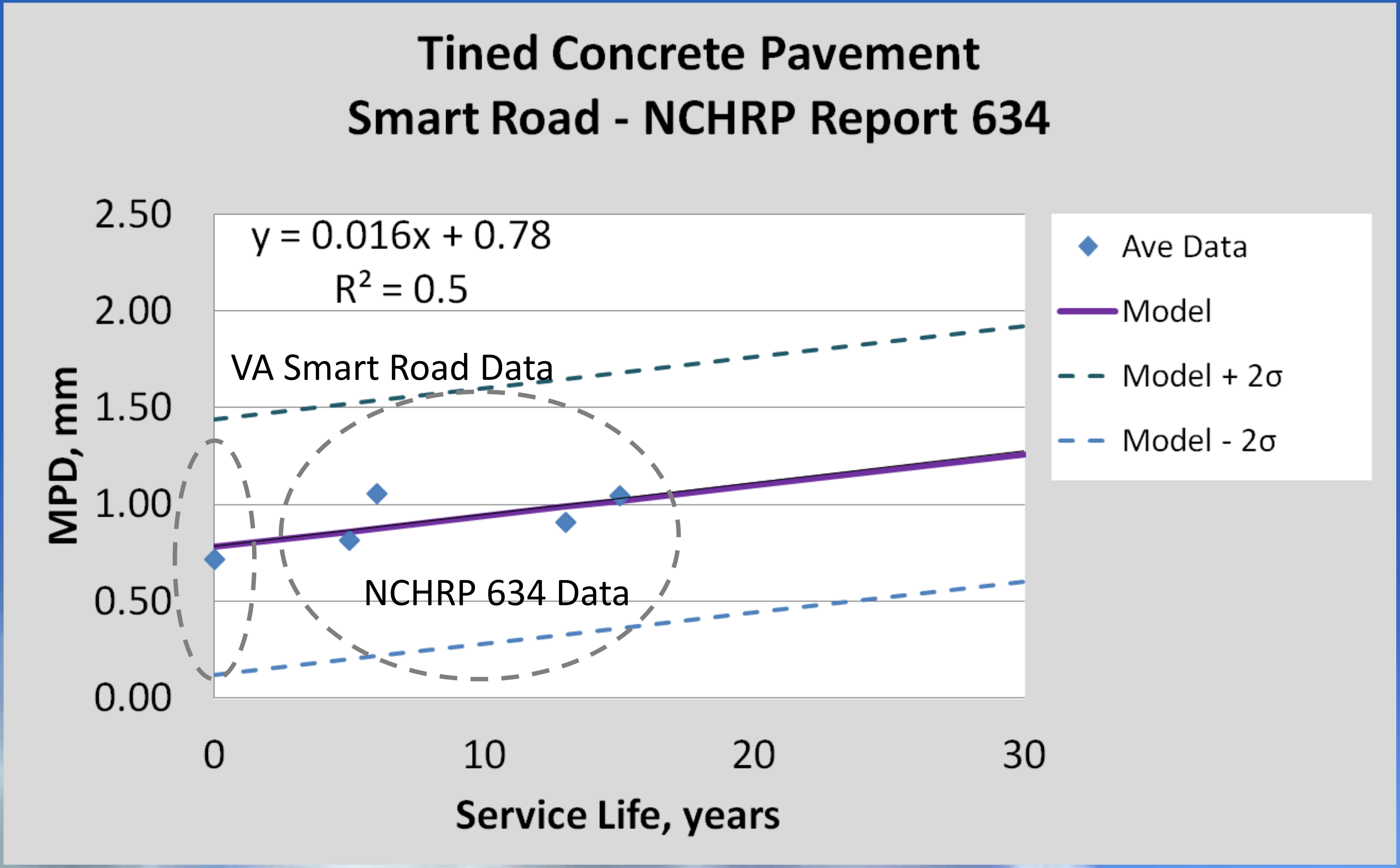
Texturing of Concrete Pavements
NCHRP 634 – 2009 Report

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

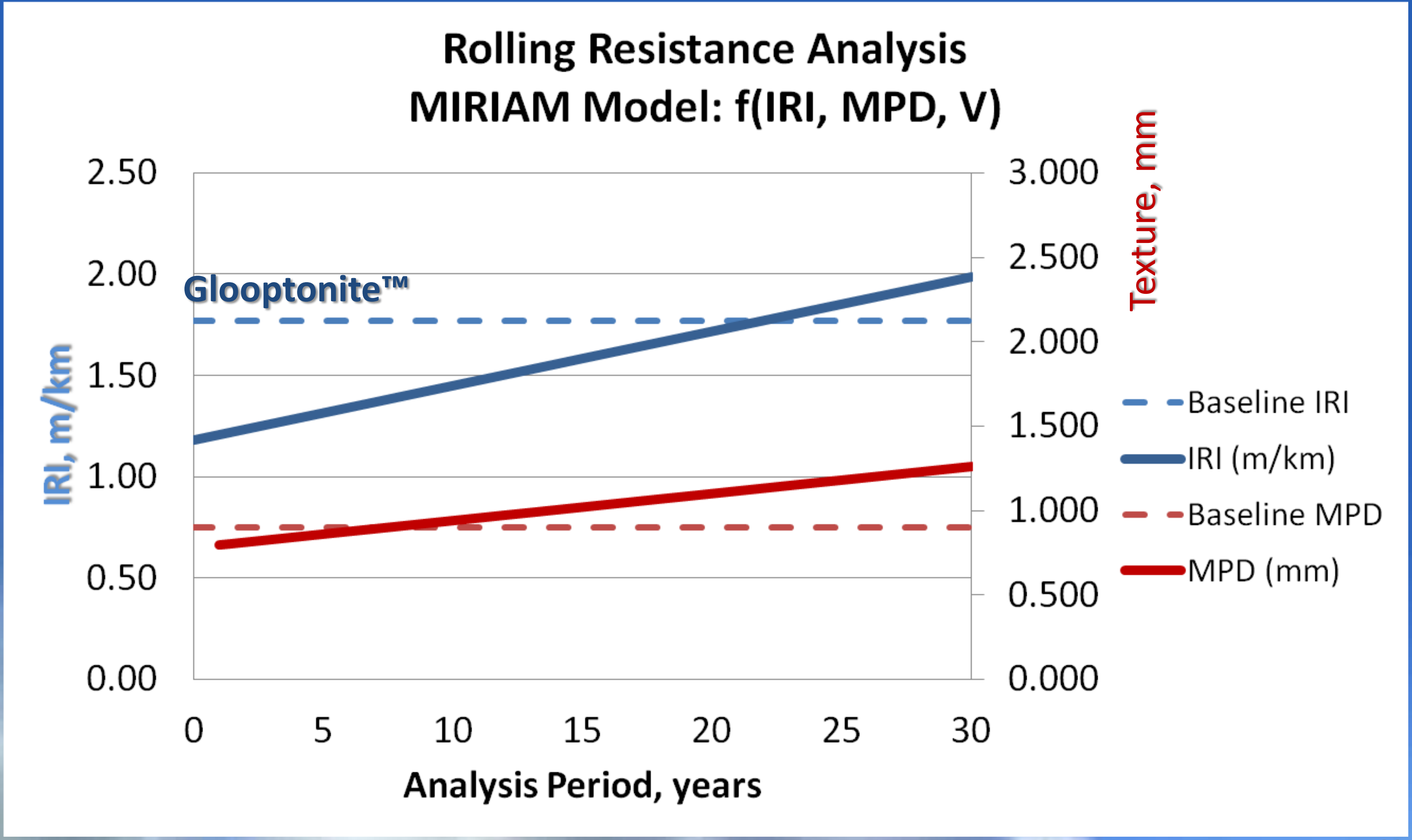




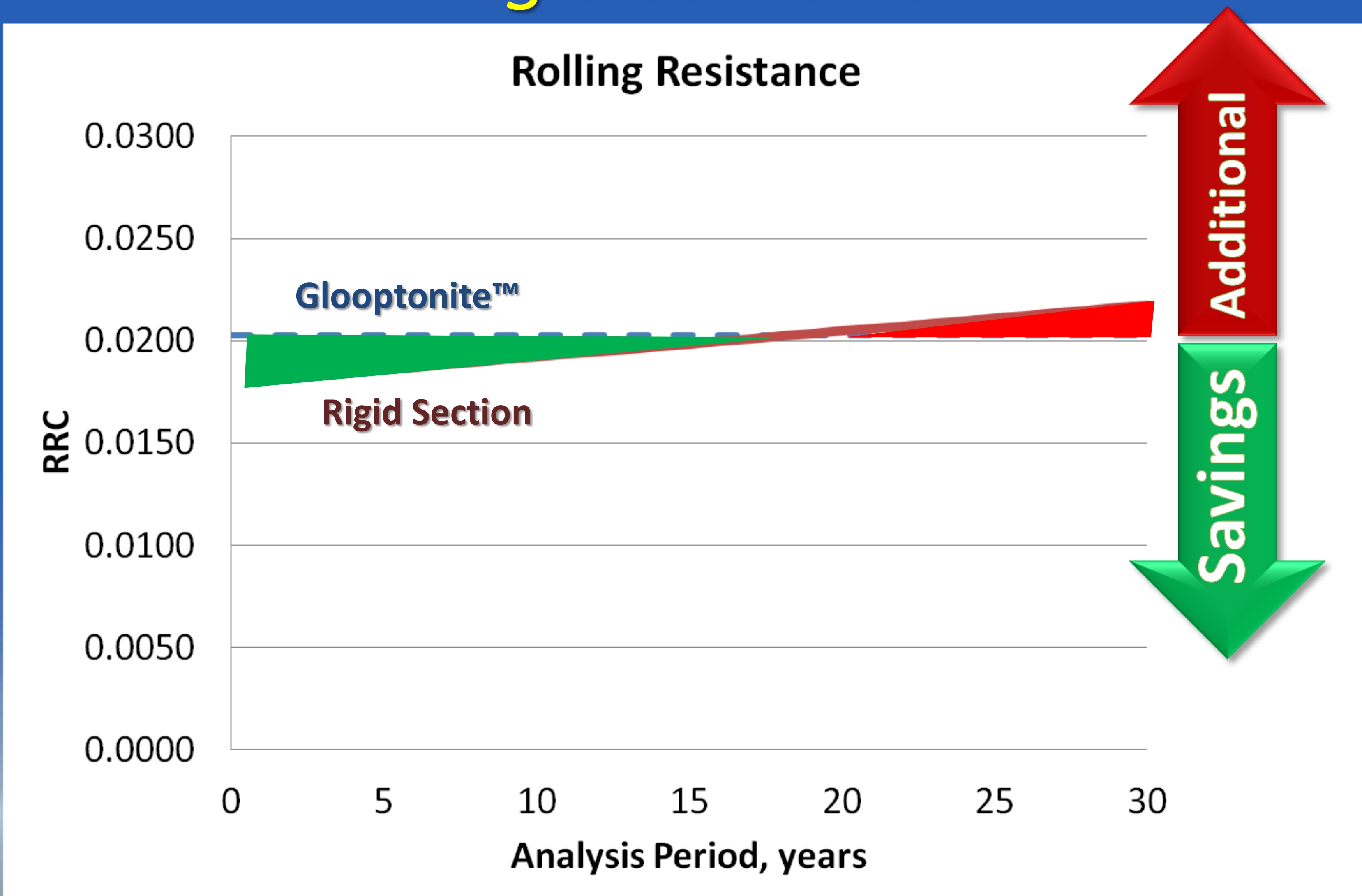
Basic Model for Tined Concrete Pavement *(Harman PCC_{Tined} Texture Model)*



RR Inputs based on
GPS-3 IRI and Harman *PCC*$_{Tined}$ Texture Model

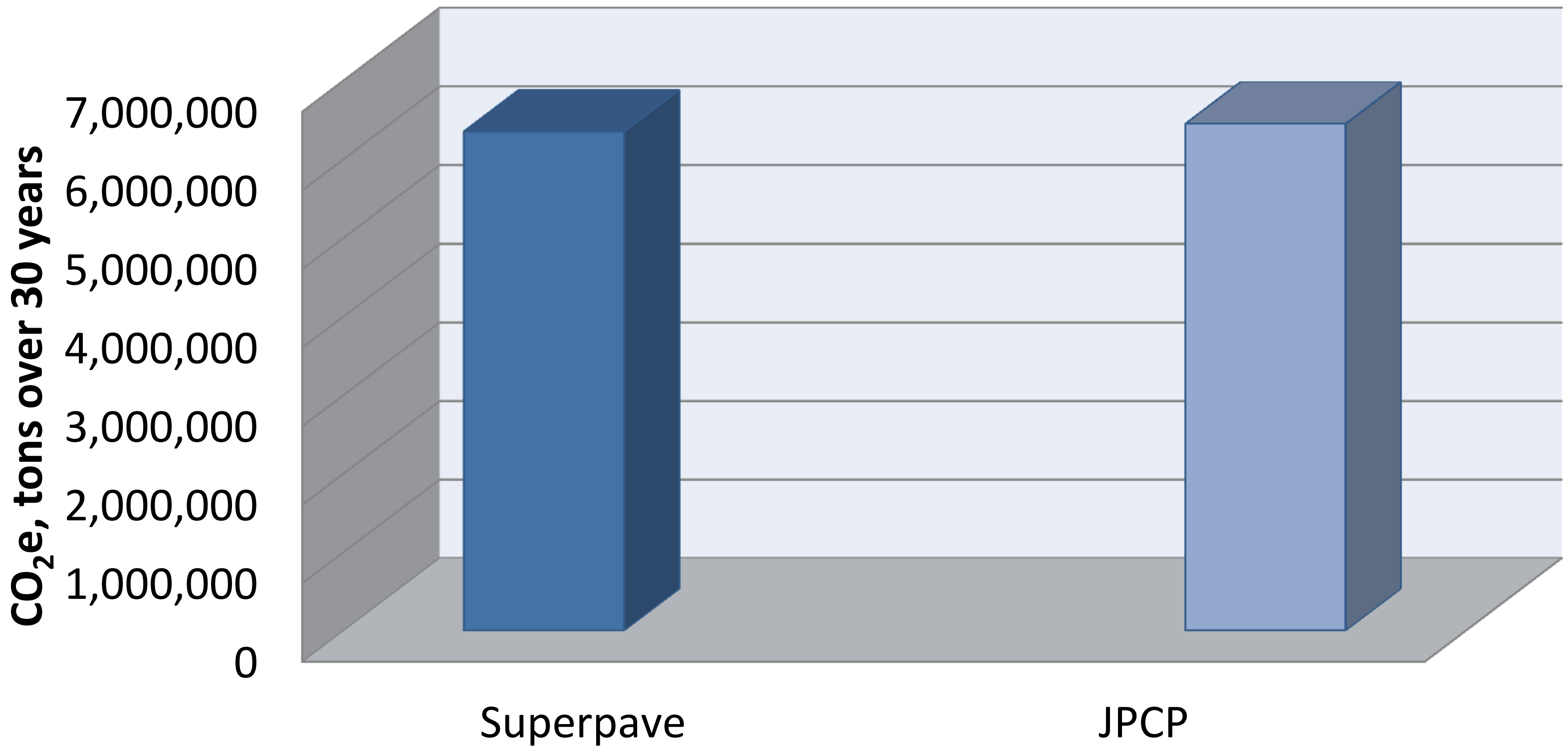


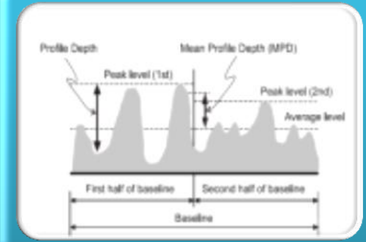
MIRIAM RRC *f*(IRI, MPD)
Rigid Scenario



- 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



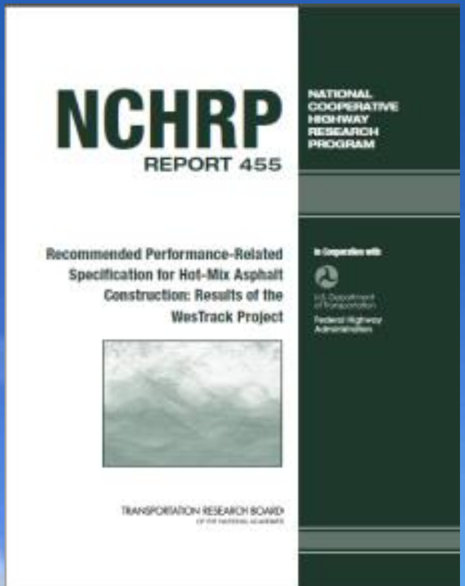


IRI / MPD MIRIAM RRC Model

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

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

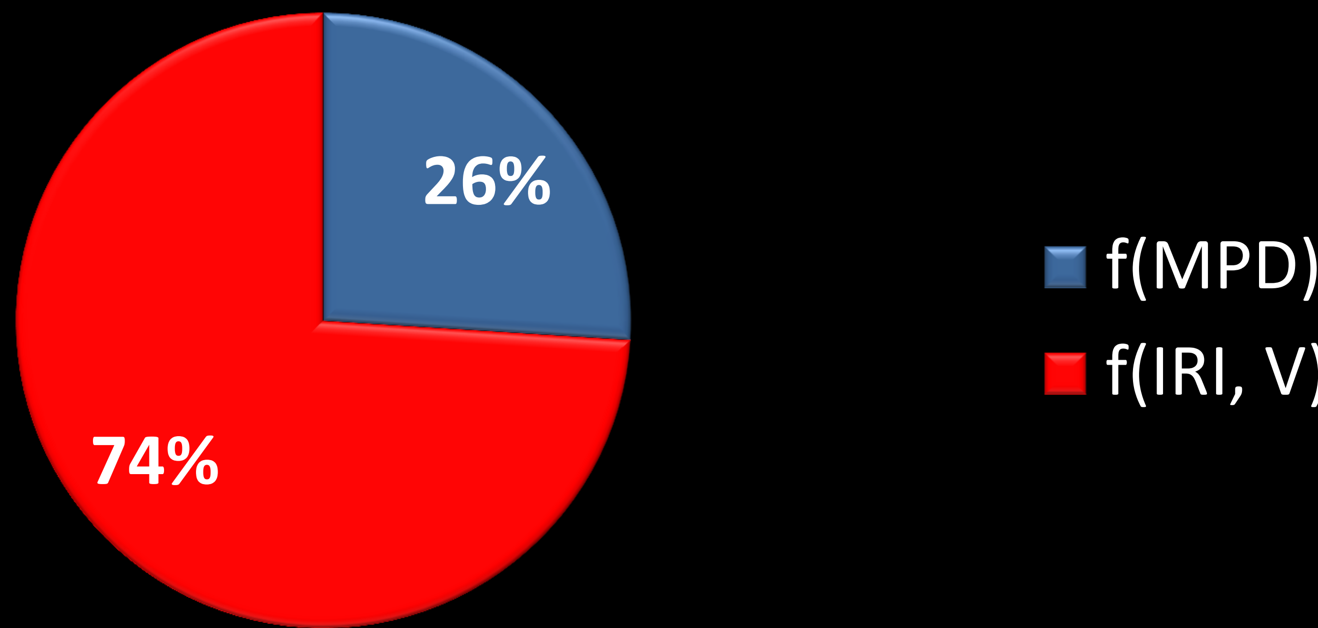
Summary of MIRIAM Models Similar to WesTrack (4.5%)

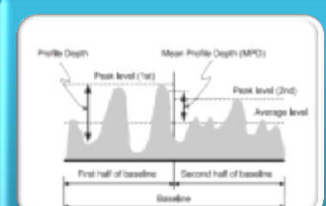
Impact of Good to Poor	Impact
Flexible Scenarios	5.0%
Rigid Scenarios	4.9%

MIRIAM Model Breakdown

Example Concrete Section 30 year Period

Contribution of Macrotexture (MPD) and Ride (IRI)

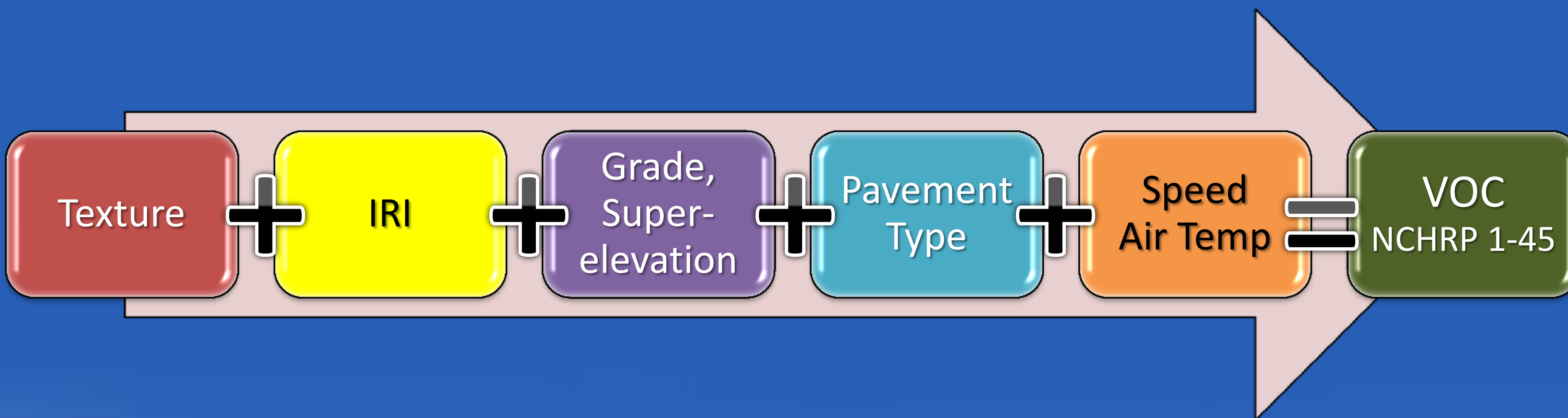




IRI / MPD MIRIAM RRC Model

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

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%	4.8% *Additional*
Fair	66%	69%	*Net 0%*
Good IRI ≤ 95 in/mile	26%	20%	2.5% *savings*

- (*) – compared to Glooptonite™ with MIRIAM

"Simple Math"

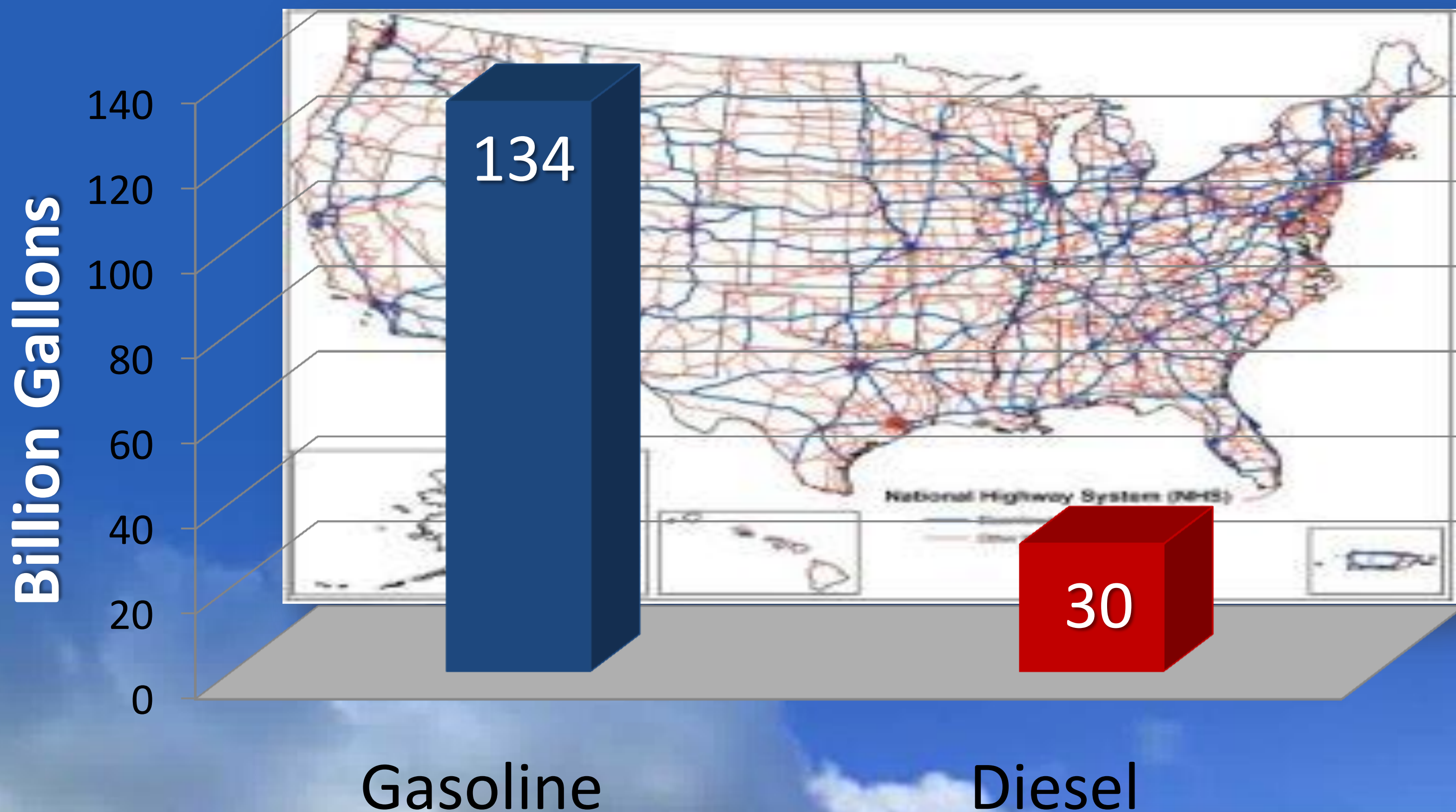
- If Fair is similar to Glooptonite™, and
  - 11% miles traveled generates 4.8% additional, and
  - 20% of miles traveled generates 2.5% less…

Net: +11%(4.8%) – 20%(2.5%) < ZERO (0%)

Poor ***Good***

$ Bottom Line $

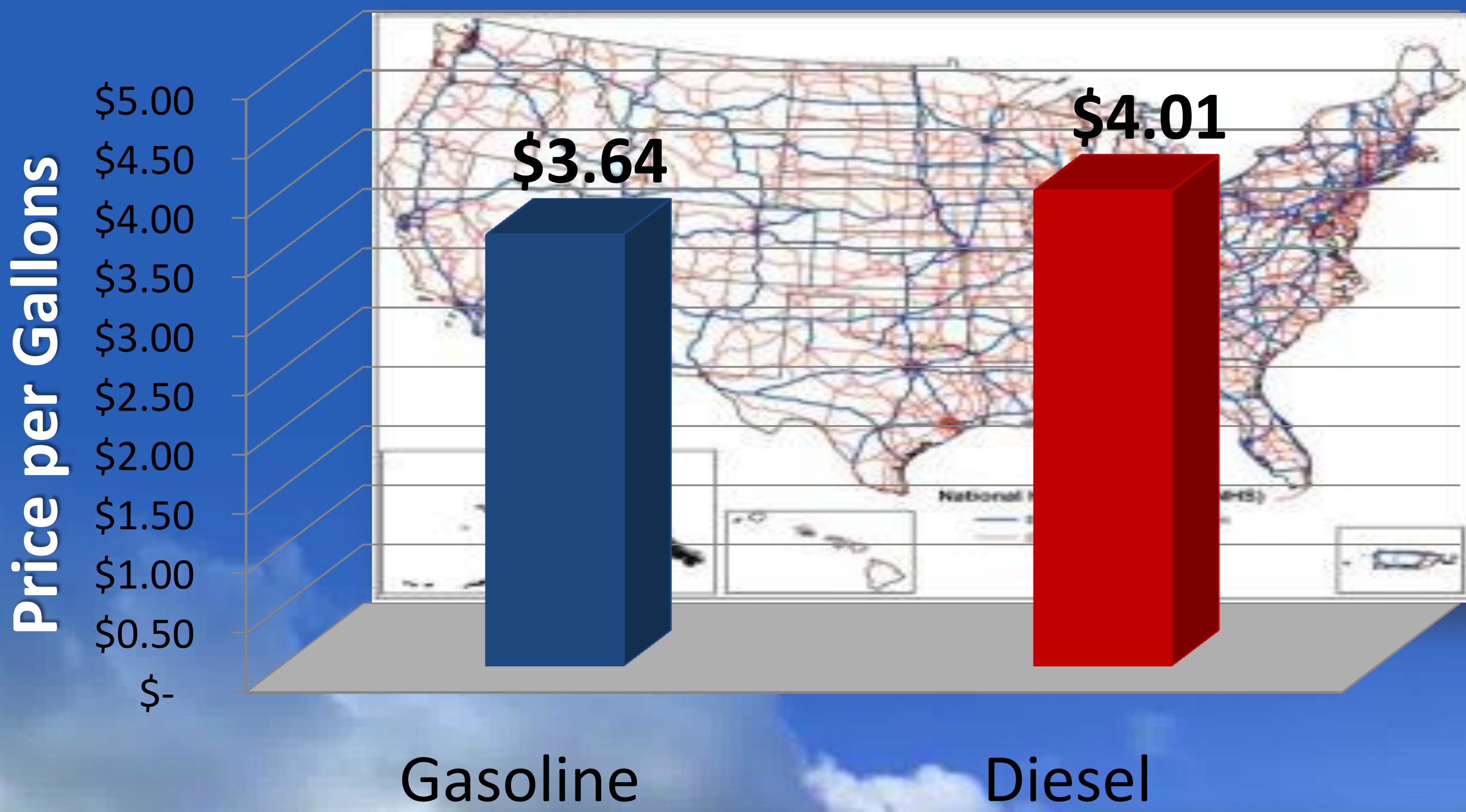
In 2011, the US consumed about…



eia Independent Statistics & Analysis
U.S. Energy Information Administration

$ Bottom Line $

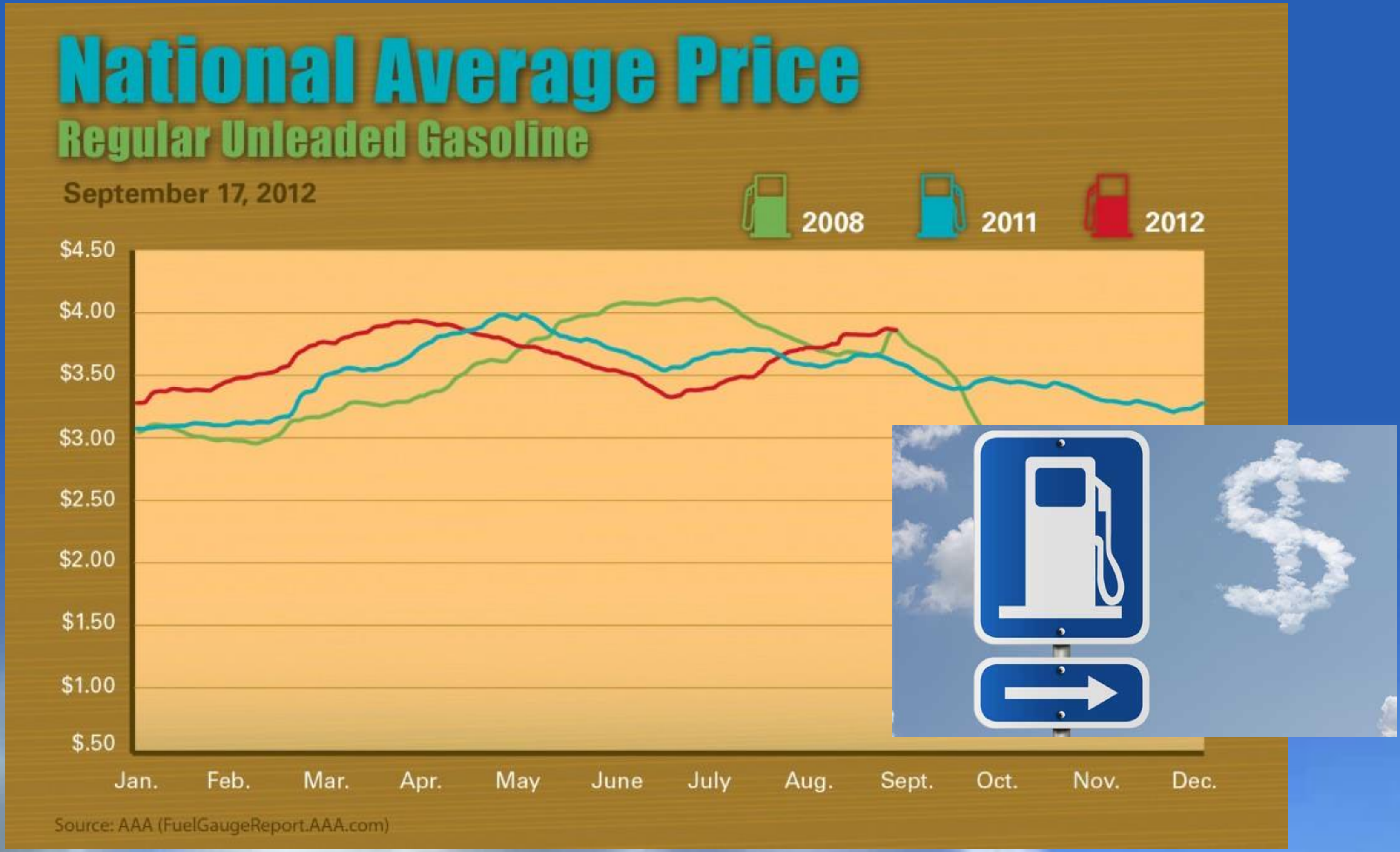
EIA projection (9/12)



eia Independent Statistics & Analysis
U.S. Energy Information Administration

AAA

September 17, 2012 national average price for a gallon of regular unleaded gasoline is **$3.86**



$ Bottom Line $

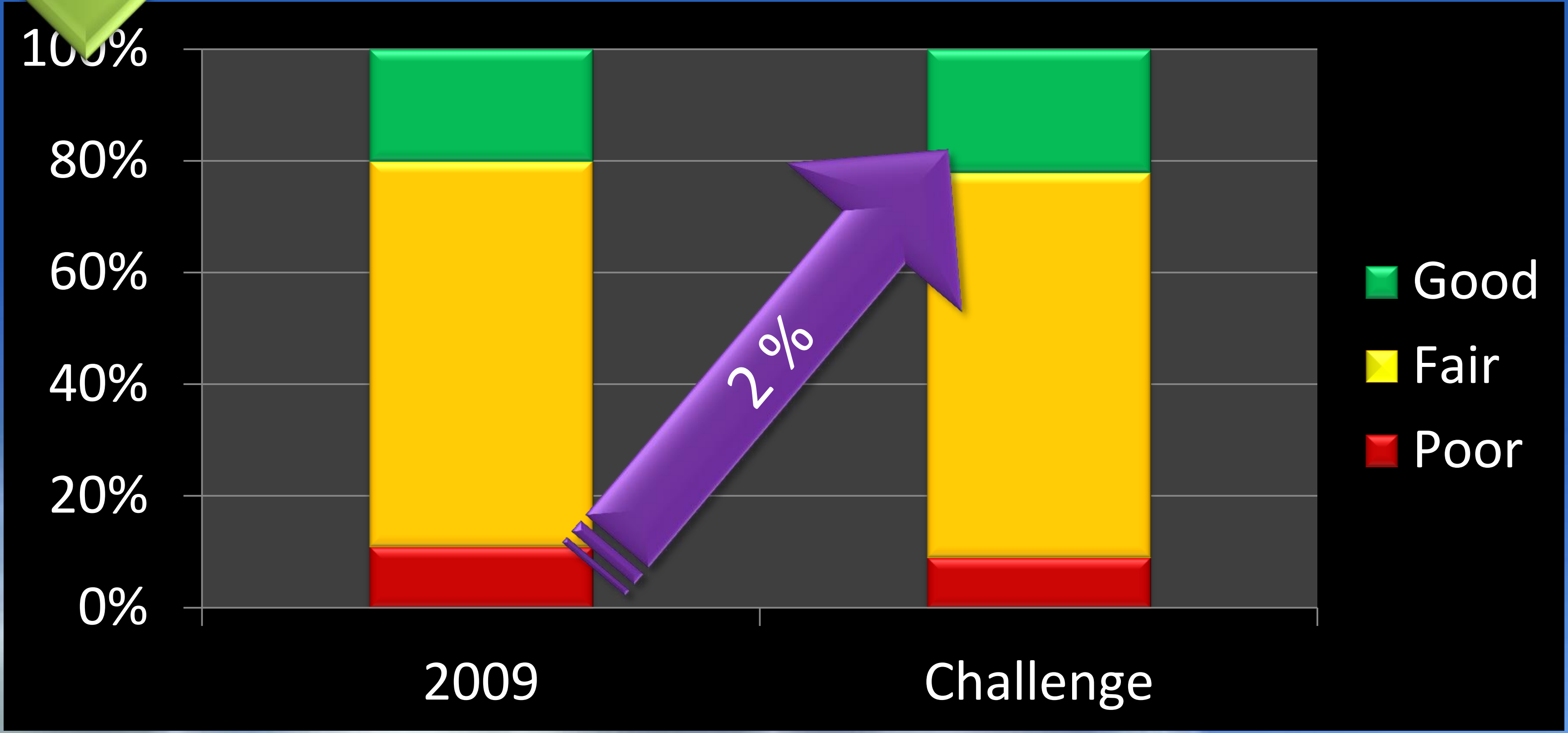
Fuel Type	Annual Usage (Gallons)	Unit Cost ($/Gallon)	Total Cost (Dollars)
Gasoline	134,000,000,000	$3.75	$500 Billion
Diesel	30,000,000,000	$4.00	$120 Billion
TOTAL			$620 Billion

Condition	~Miles Traveled	% Change
Poor IRI > 170 in/mile	11%	*-2%*
Fair	69%	
Good IRI ≤ 95 in/mile	20%	*+2%*

Potential Return on Investment
Step 1

1

- **In addition to maintaining the current condition**
- Increase **GOOD by 2%↑** & Decrease the **POOR by 2%↓**



Potential Return on Investment
Step 2

2

- 2% of the **POOR** 2009 NHS is 3,200 c.l. miles
- ~$577,000 rehab cost per c.l. mile(*)

- 160,000 miles x 2% = 3,200 c. l. miles

x $577,000 / c.l. mile

(*) – Rehab Cost based on FL DOT 2012 Urban Interstate Asphalt Costs
Mill & Resurface 3 Lane Urban Road with Center Turn Lane and 4' Bike Lanes

Potential Return on Investment
Step 3

3

- Required increased investment ~ $1.85B
- Annual fuel savings $900M
- Realized Benefit over **GOOD** Life (~9 yrs) ~ $8B (fuel savings)

$900M / yr
$avings

Potential Return on Investment
Step 4

4

- Total Return on Investment over 9 yrs ~ 440%

- Pretty cool, but…

Yes, this is two separate pockets of money…

$1.85B increase Highway Funding

$8B Public Savings Fuel

Where are the greatest potentials, <u>within our control</u>, for reducing environmental impacts???


THANK YOU


2
1
3

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