E N G I N E E R I N G

Pavement Life Cycle Assessment Workshop
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Effect of Pavement Conditions on Rolling Resistance and Fuel Consumption

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CIVIL & ENVIRONMENTAL ENGINEERING

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What do we mean by driving resistance and rolling resistance?

- air resistance
- rolling resistance
- inertial resistance
- gradient resistance
- side force resistance
- transmission losses
- losses from the use of auxiliaries
- engine friction

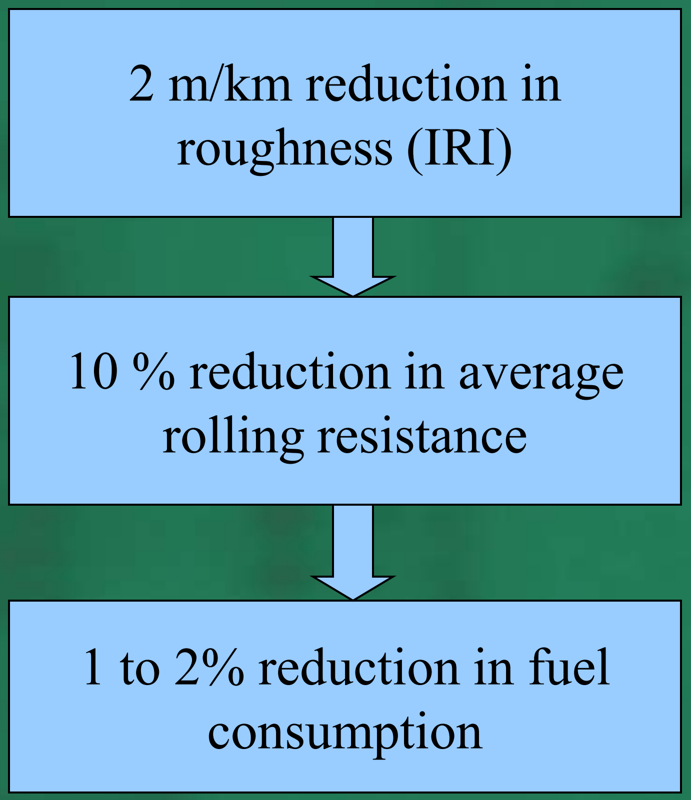
Factors affecting rolling resistance

- **Most important factors in rolling resistance:**
  - Vehicle weight
  - Tire inflation
- **Less important:**
  - Vehicle speed
- **Least important:**
  - Tire tread design, composition and width
  - Tire temperature
  - Road structure and conditions

Influence of IRI and MPD on RR (Sandberg, 1997)

- Results of coast-down measurements on 34 test sections
- Increases in car RR based on ECRPD results
  - at speed of 54 km/h:
    - IRI from 1 to 10 m/km: increase in RR by 19 %
    - MPD from 0.3 to 3 mm: increase in RR by 46 %
  - at speed of 90 km/h:
    - IRI from 1 to 10 m/km: increase in RR by 48 %
    - MPD from 0.3 to 3 mm: increase in RR by 72 %

Effect of IRI and MPD on fuel consumption (TRB special report 286)



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Gaps in knowledge

- The understanding of the relationship between pavement surface characteristics and vehicle fuel consumption is still in development.
- Current models require improvement.

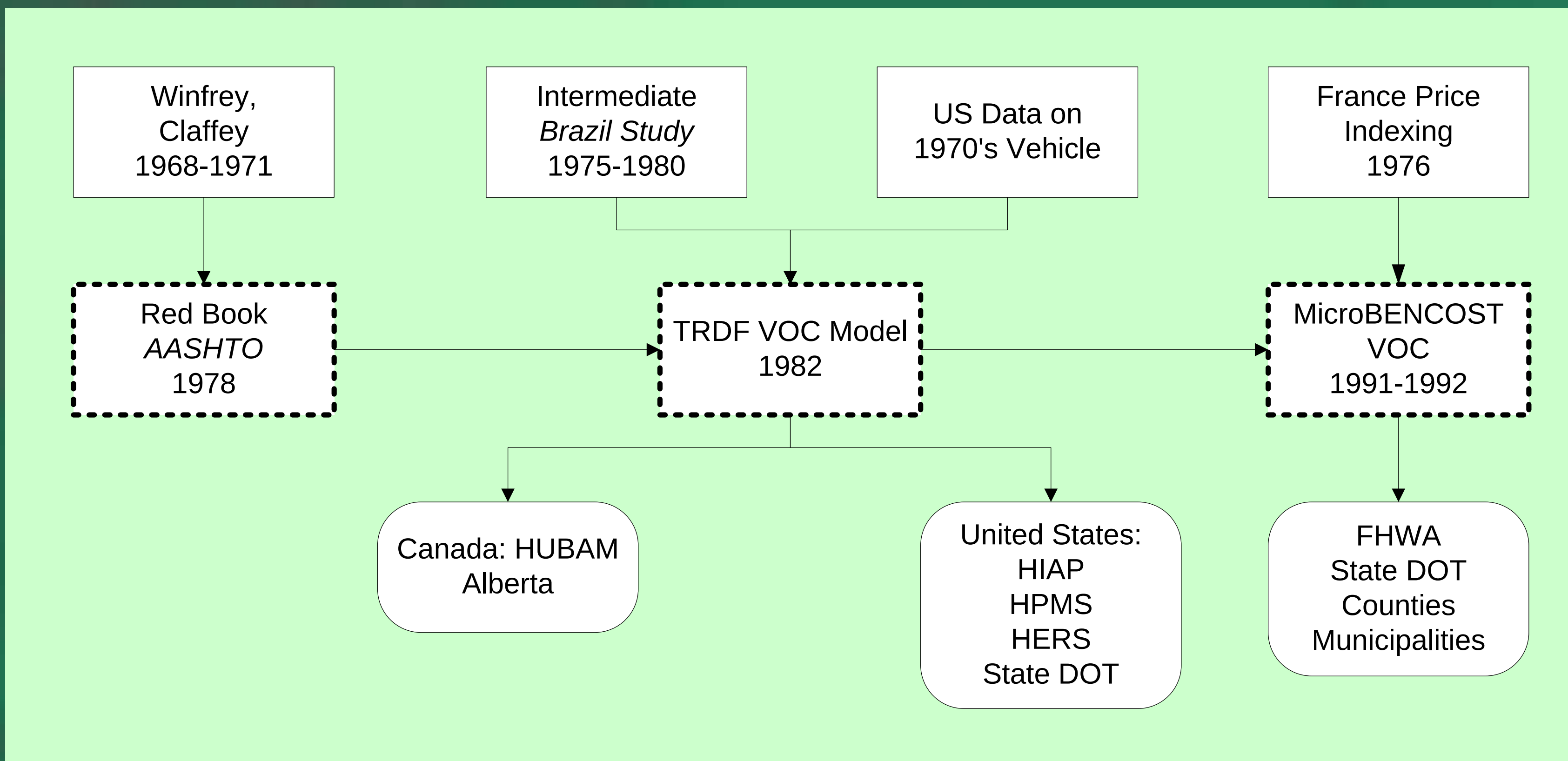
NCHRP 1-45 : Effect of pavement conditions on fuel consumption

- Recommend **models** for estimating the **effects** of pavement **surface condition** on **VOC**. These models should be able to:

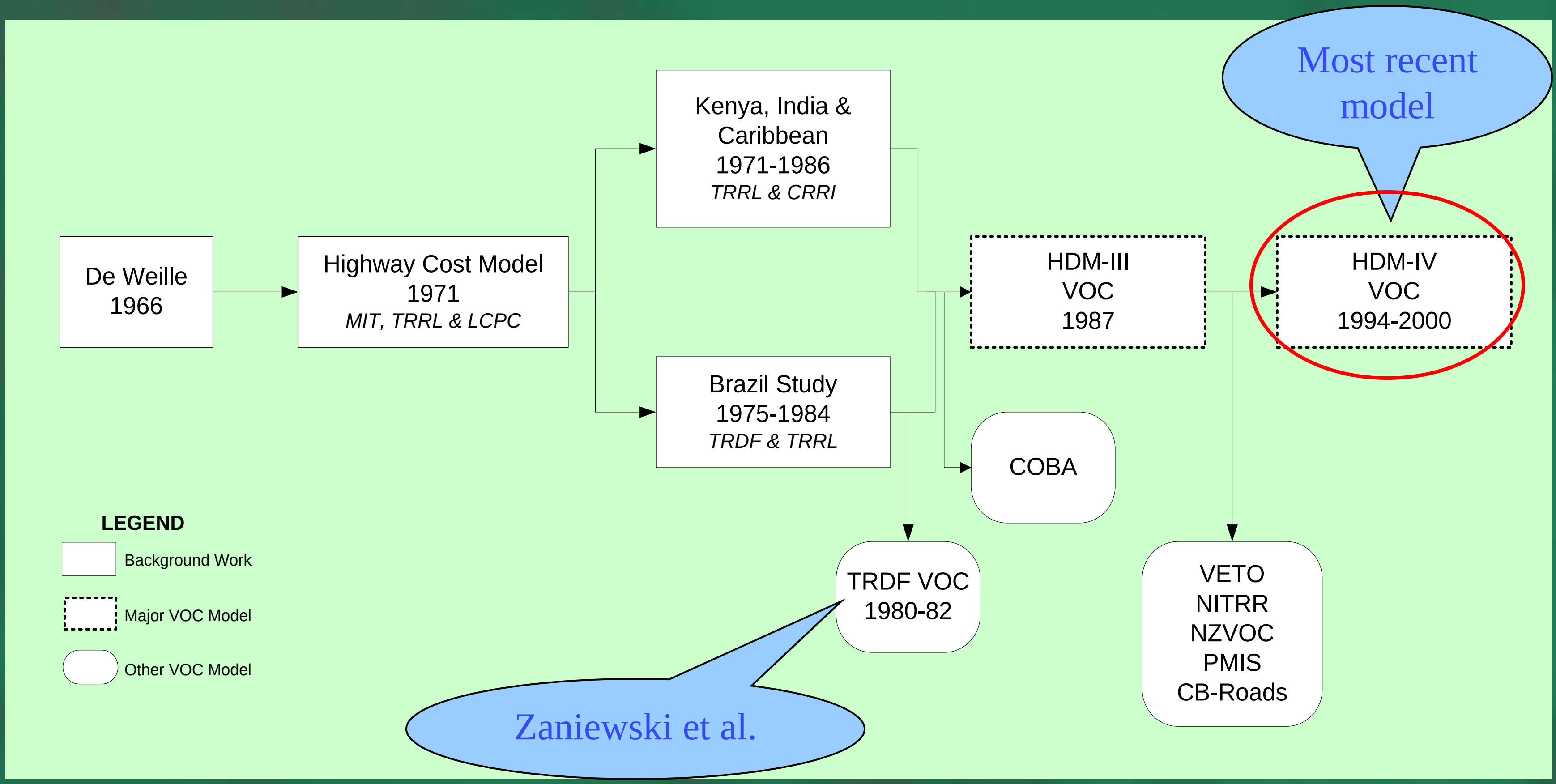
    a) Take into account pavement, traffic and environmental conditions encountered in the US

    b) Address the full range of vehicle types

United States VOC Models Development



World Bank VOC Models Development



Source: HDM IV manual

HDM 4 Model

$$IFC = f\left(Ptr, Paccs + Peng\right)$$

P_{tr}	= Power required to overcome traction forces (kW)
P_{accs}	= Power required for engine accessories (e.g. fan belt, alternator etc.) (kW)
P_{eng}	= Power required to overcome internal engine friction (kW)

HDM 4 model (cont.)

$$P_{tr} = \frac{v\left(F_a + F_g + F_c + F_r + F_i\right)}{1000}$$

Tractive power

$$Fa = 0.5 * \rho * CDmult * CD * AF * \upsilon^2$$

Aerodynamic forces

$$Fg = M * GR * g$$

Gradient forces

$$Fc = \max\left(0, \frac{\left(\frac{M * \upsilon^2}{R} - M * g * e\right)^2}{Nw * Cs} * 10^{-3}\right)$$

Curvature forces

$$Fr = CR2 * FCLIM * \left(b11 * Nw + CR1 * \left(b12 * M + b13 * \upsilon^2\right)\right)$$

Rolling resistance

$$CR2 = Kcr2\left[a0 + a1 * Tdsp + a2 * IRI + a3 * DEF\right]$$

Surface factor

$$Fi = M * \left(a0 + a1 * \arctan\left(\frac{a2}{\upsilon^3}\right)\right) * a$$

Inertial forces

Field tests matrix

Section ID	Pavement Type		IRI range (m/Km)	Length (Km)	Speed limit (Km/h)	Test Speed (Km/h)		Replicates
	AC	PCC						
AB	X		1.3 - 8.5	1.44	72	56	72	2
BC	X		1.7 - 7	1.6	72	56	72	2
DE	X		3.5 - 6	0.48	72	56	72	2
EF	X		3.3 - 6	0.64	72	56	72	2
GH		X	1.1 - 2.5	4.8	112	88	104	2
JI		X	1.5 - 2.6	6.4	80	56	72	2
IJ1		X	1.5 - 2.6	0.64	80	72	88	2
IJ2	X			1.6	80	56	72	2
IJ3		X	0.8 - 4.6	0.48	80	56	72	2
IJ4		X		1.28	72	56	72	2

Data acquisition system

- The data acquisition system could access and log data from the vehicle’s Engine Control Unit (ECU) via On Board Diagnostic (OBD) connector

Profile and Texture Measurements: MDOT test vehicles

Rapid Travel Profilometer
This vehicle measures the ride quality or smoothness of pavements. Operating at highway speeds, it uses a laser to measure the profile of the roadway and an accelerometer to determine the movement of the truck.

Road Surface Analyzer
This equipment computes a Mean Profile Depth (MPD) based on the ASTM Standard E1845

Slope surveys: High Precision GPS

- The sampling rate is every 1 second at highway speed (every 100ft).
- The average error is 0.5 inch per 0.3 miles,

Loading conditions

Light truck	Heavy truck
	
6,210 lb	47,000 lb

Calibration of the HDM 4 fuel consumption model

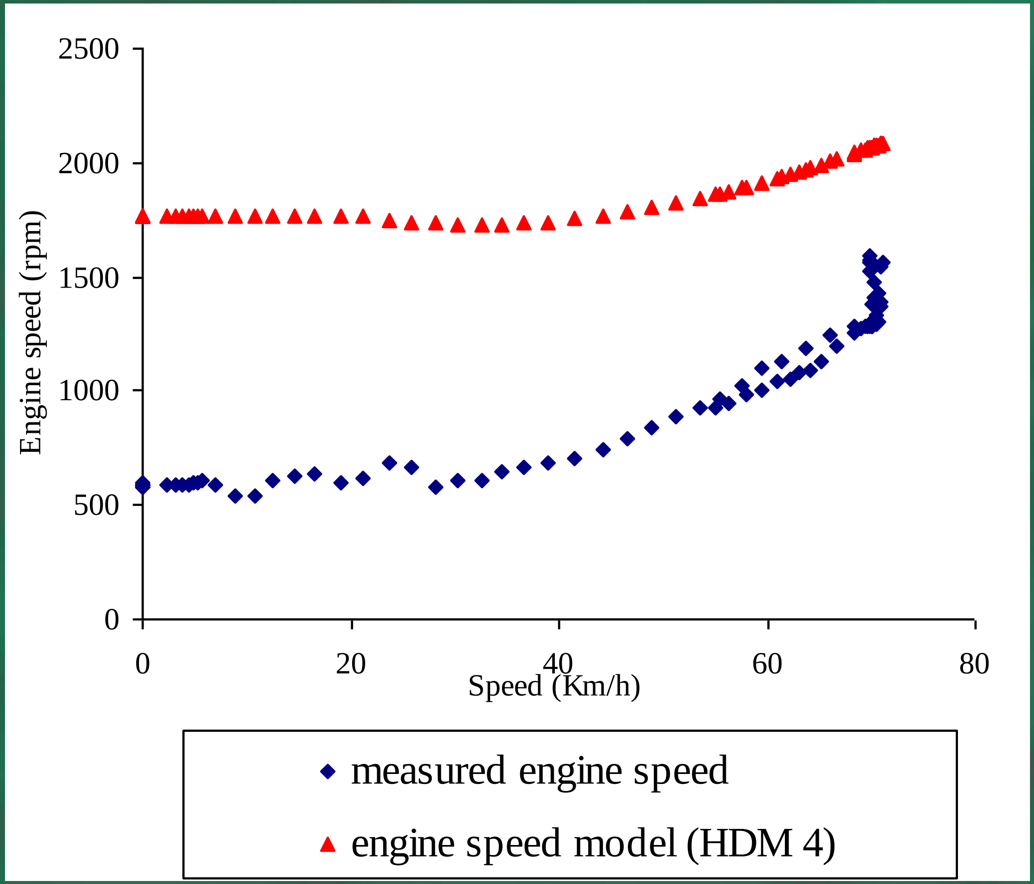
Engine and accessories power

$$Pengaccs = Peng + Paccs$$
$$= KPea * P\max * \left(Paccs\_a1 + (Paccs\_a0 - Paccs\_a1) * \frac{RPM - RMPIdle}{RPM100 - RPMIdle}\right.$$

Rolling resistance Surface factor

$$CR2 = Kcr2\left[a0 + a1 * Tdsp + a2 * IRI + a3 * DEF\right]$$

Effect of engine speed prediction errors on the calibration



Overestimation of the engine speed

Overestimation of the engine and accessories power

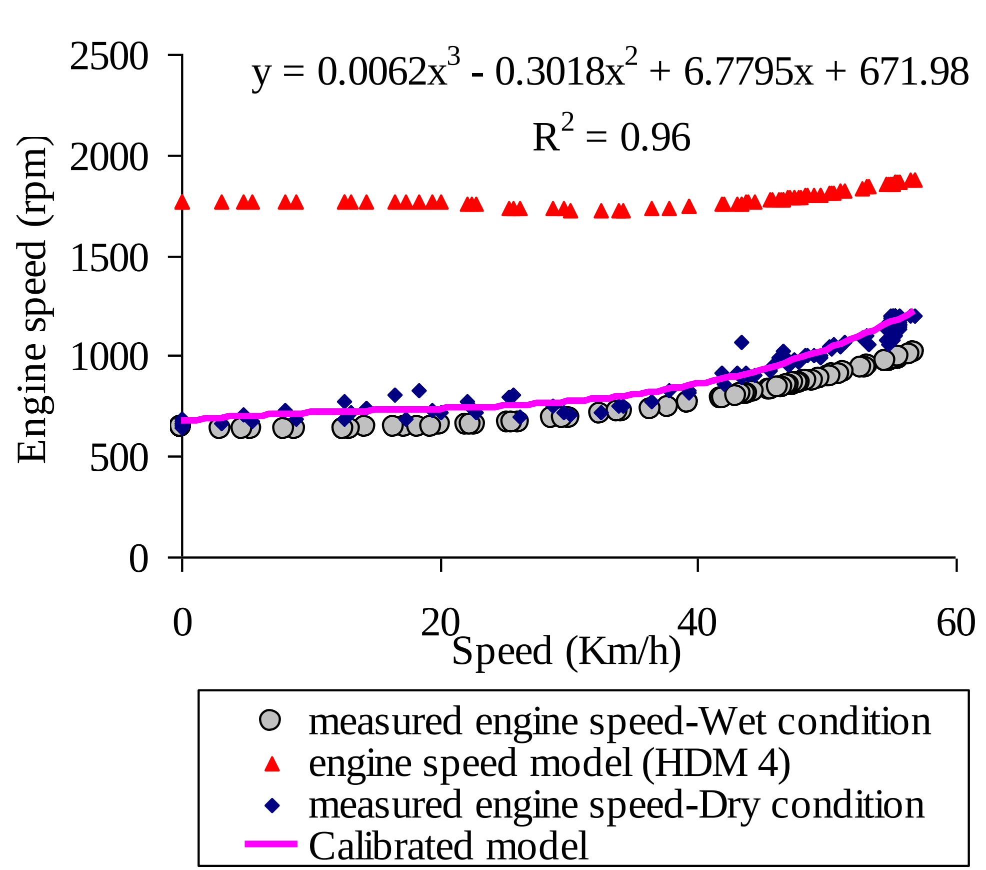
Underestimation of the traction power

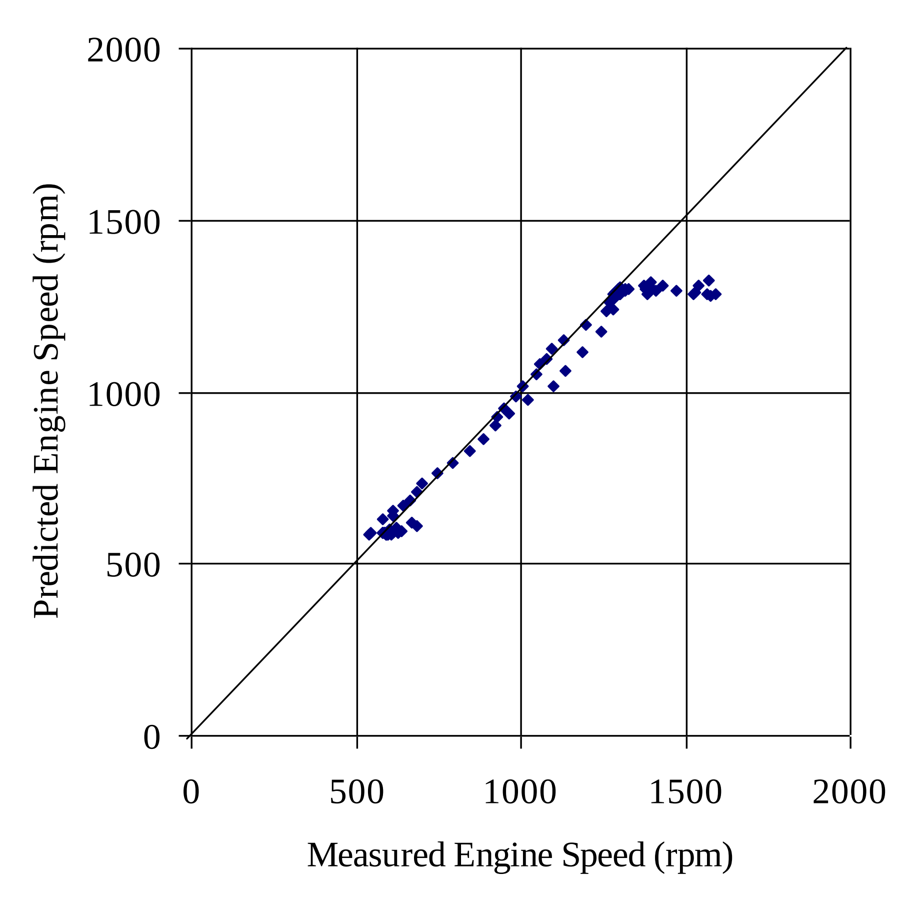
=

Underestimation of the effect of pavement conditions

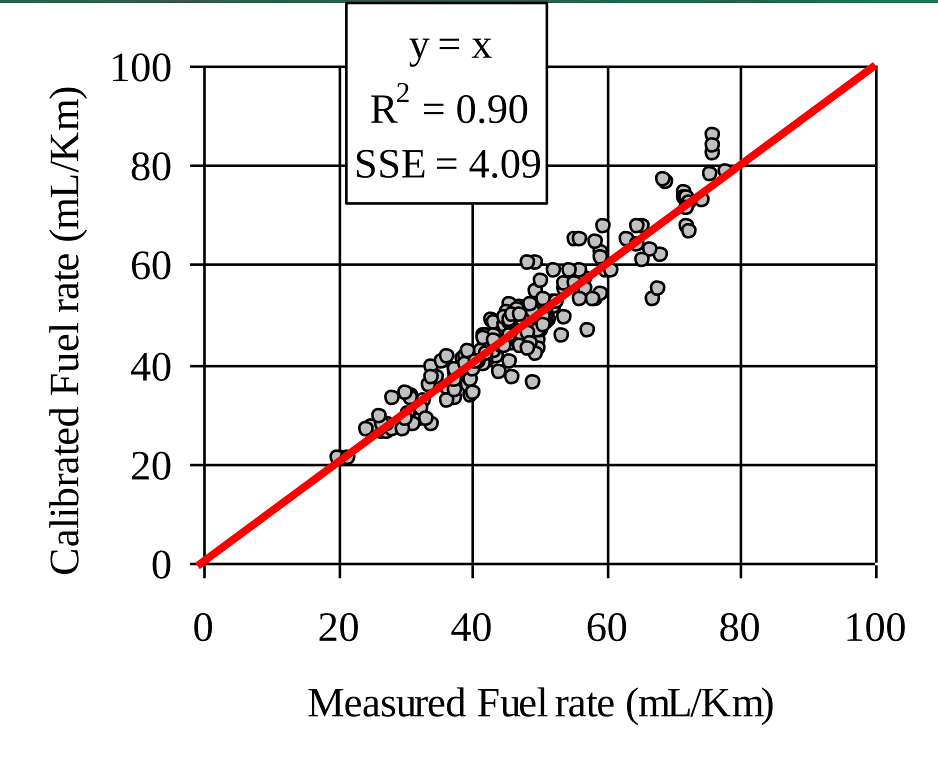
Calibration of the HDM 4 engine speed model

Van

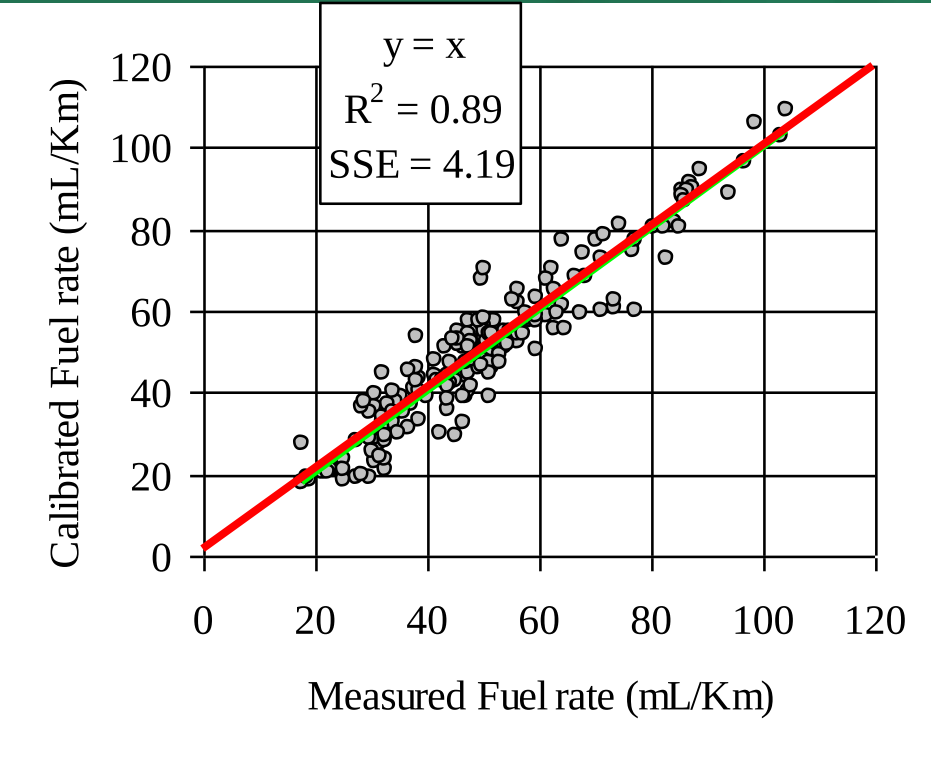




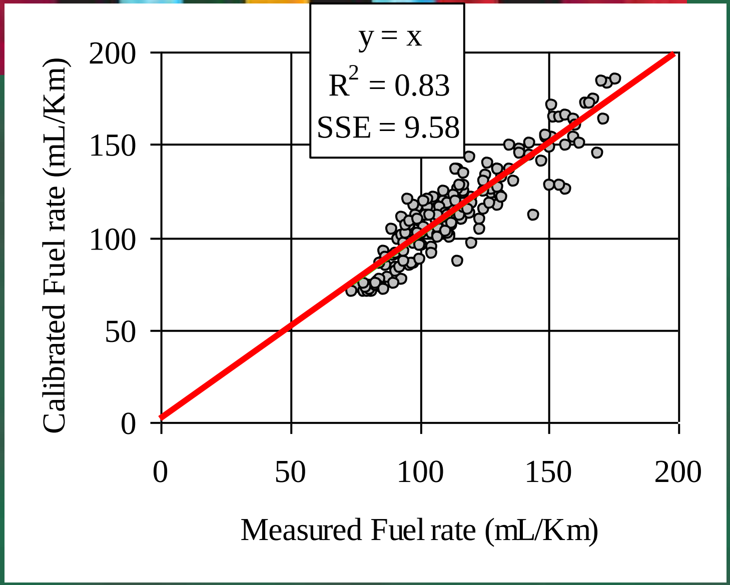
Observed fuel consumption versus estimated after calibration



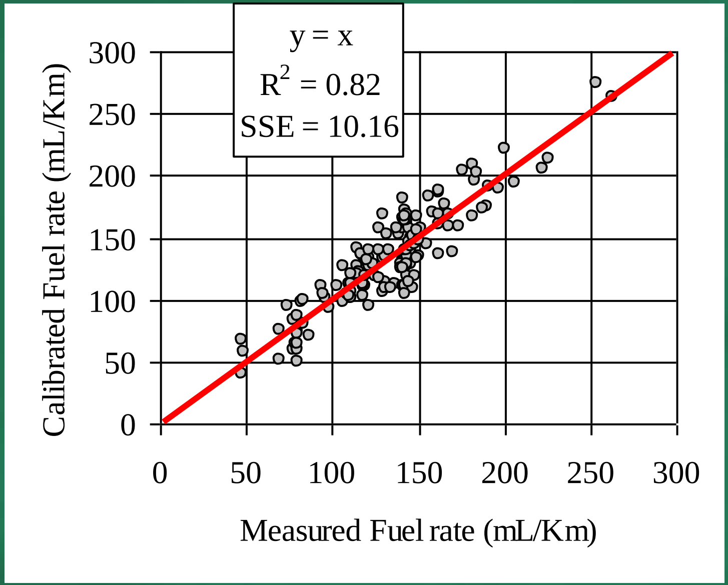
Passenger car



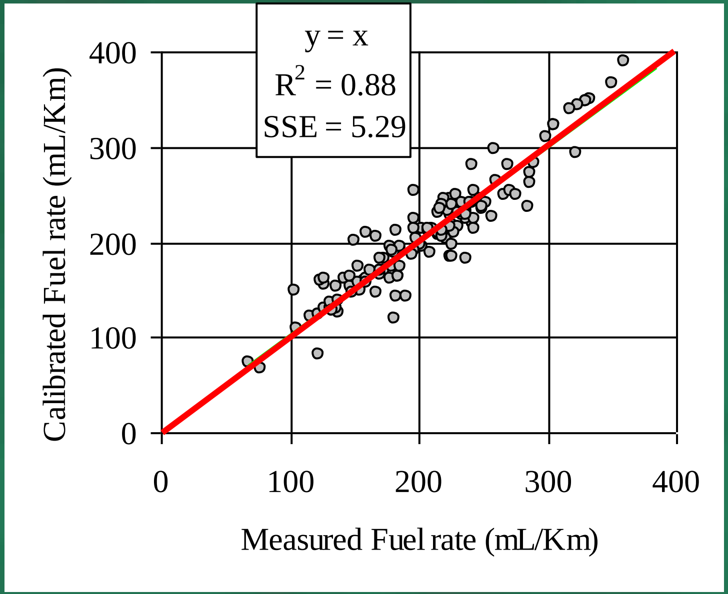
SUV



Van



Light truck



Articulated truck

Heavy Truck: Analysis of covariance at 55 mph

Tests of Between-Subjects Effects

Dependent Variable:FC_mLKm

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4300.769[a]	14	307.198	769.817	.000
Intercept	19697.944	1	19697.944	49361.721	.000
IRI	23.557	1	23.557	59.032	.000
Texture	.147	1	.147	.368	.545
Grade	3796.846	12	316.404	792.887	.000
Error	48.684	122	.399		
Total	351401.815	137			
Corrected Total	4349.454	136			

a. R Squared = .989 (Adjusted R Squared = .988)

Heavy truck: Analysis of covariance at 35 mph

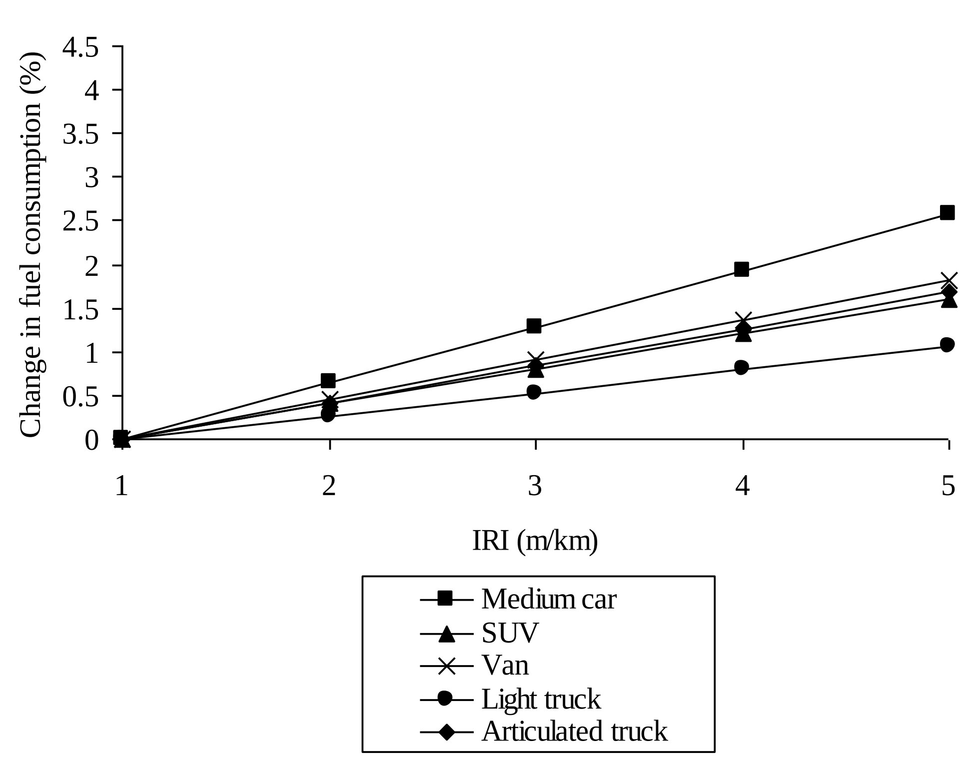
Tests of Between-Subjects Effects

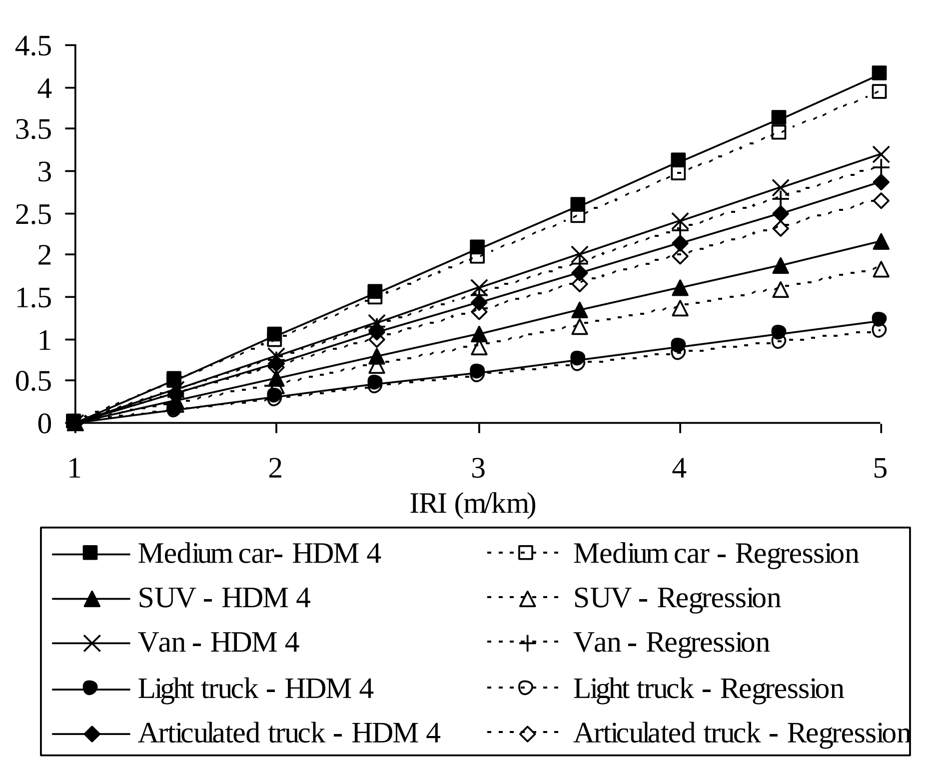
Dependent Variable:FC_mLKm

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	138113.100[a]	13	10624.085	2077.841	.000
Intercept	335375.546	1	335375.546	65592.193	.000
IRI	500.674	1	500.674	97.921	.000
Texture	23.920	1	23.920	4.678	.032
Grade	123056.405	11	11186.946	2187.924	.000
Error	628.904	123	5.113		
Total	5525978.735	137			
Corrected Total	138742.004	136			

a. R Squared = .995 (Adjusted R Squared = .995)

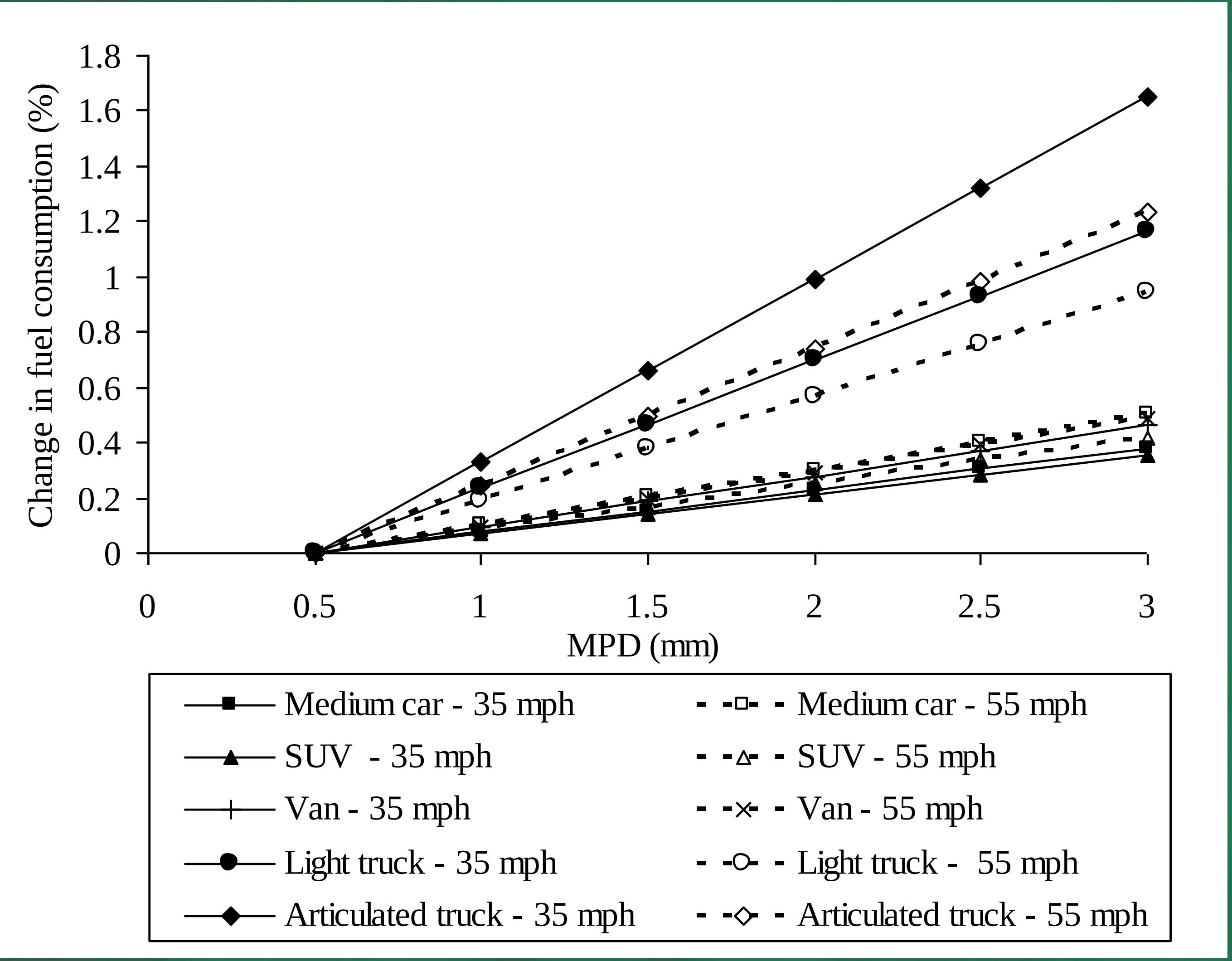
Effect of roughness: HDM 4 versus regression data





Before calibration **After calibration**

Effect of Texture on Fuel Consumption - Regression



Effect of pavement type on fuel consumption

- Conduct univariate analysis having IRI as a covariate and pavement type as fixed factor
- Repeat the analysis for 35, 45 and 55 mph

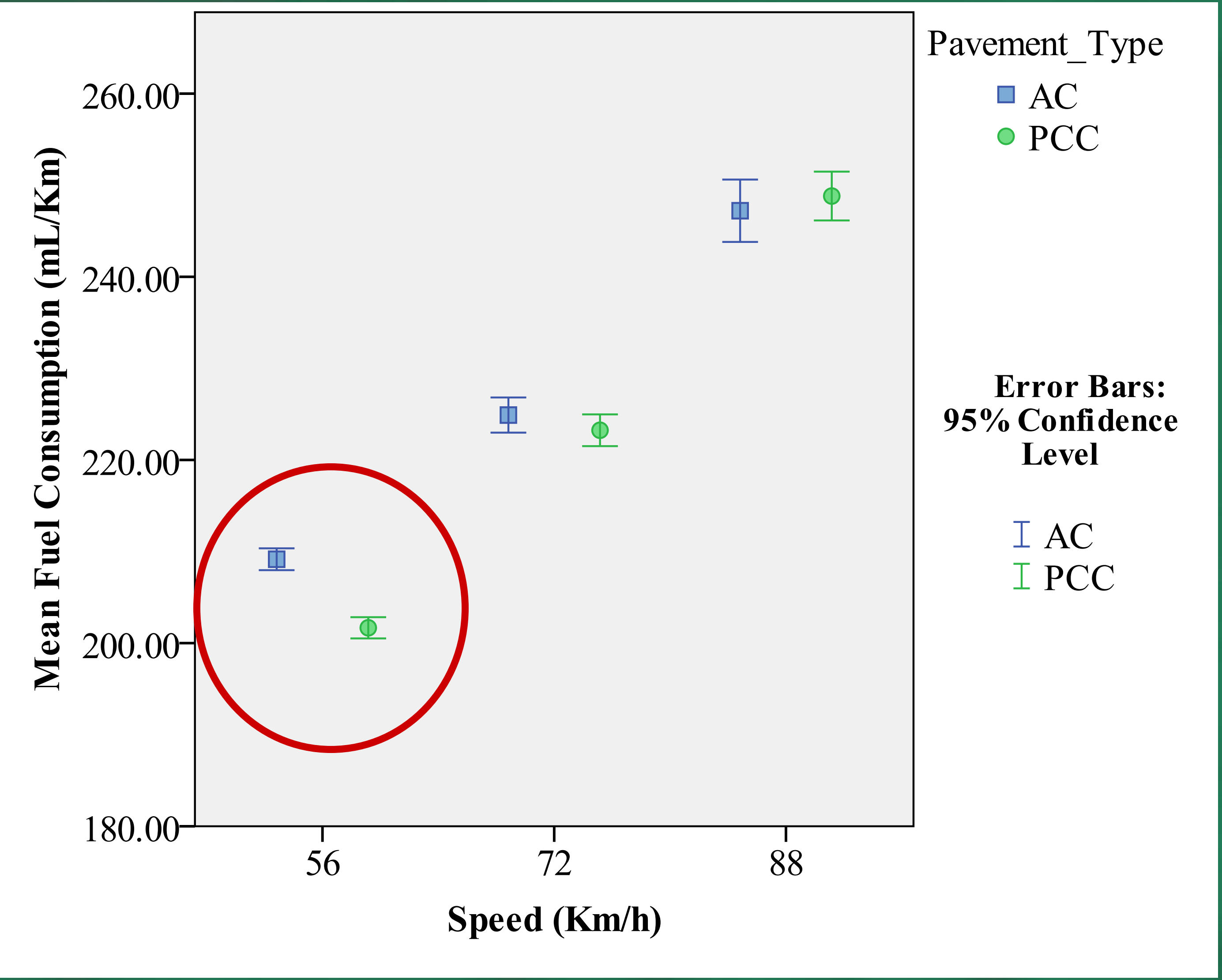
Effect of pavement type on fuel consumption

	Summer		Winter	
	Sig.	Not Sig.	Sig.	Not Sig.
Passenger Car		√		√
VAN		√		√
SUV		√		√
Light Truck	√*	√†		√
Articulated Truck	√*	√†		√

* Trucks driven over AC at 35 mph consumes more than trucks driven over PCC

† not significant at 45 and 55 mph

Articulated truck



Part I
Summary and conclusions

- Field tests as part of NCHRP 1-45 confirmed the effect of roughness on fuel consumption and allowed for calibration and validation of the HDM 4 FC model.
- Effect of texture depth on fuel consumption could only be seen for heavy truck at low speed (35 mph)
- Effect of pavement type could only be seen in summer conditions, only for trucks and only at low speed (35 mph)

Part II:
Effect of Roughness on Repair and Maintenance Costs

HDM 4 Repair and Maintenance Model

- HDM4 Repair and Maintenance Cost model is empirical.
- HDM-4 model was calibrated using data from developing countries (e.g., Brazil, India).
  - Labor hours are much higher than in the US
  - The inflation in the parts and vehicle prices between the US and developing countries.

HDM 4 repair and maintenance costs model

- Parts consumption

$$PARTS = \left(K0_{pc}\left[CKM^{kp}\left(a_0 + a_1\ RI\right)\right] + K1_{pc}\right)\left(1 + CPCON \times dFUEL\right)$$

$$RI = \max\left(IRI, \min\left(IRI_0, a_4 + a_5 * IRI^{a6}\right)\right)$$

$$a_4 = IRI0 - a_7$$

$$a_5 = \frac{a_7}{IRI0^{\frac{IRI0}{a7}}}$$

$$a_5 = \frac{IRI0}{a_7}$$

$$a_7 = IRI0 - 3$$

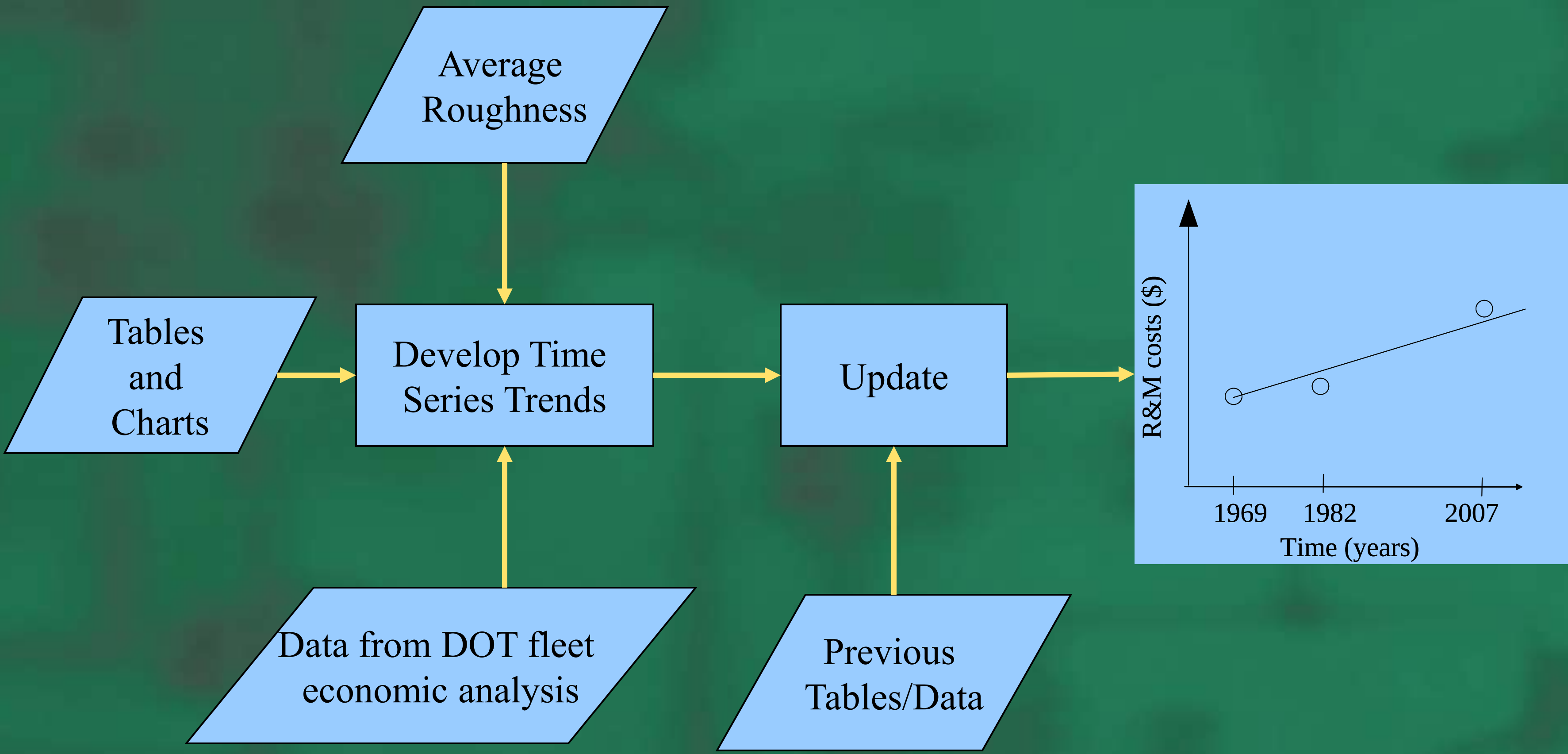
$$IRI0 = 3$$

Smoothing equation

- Labor hours

$$LH = K0_{lh}\left(a_2 \times PARTS^{a3}\right) + K1_{lh}$$

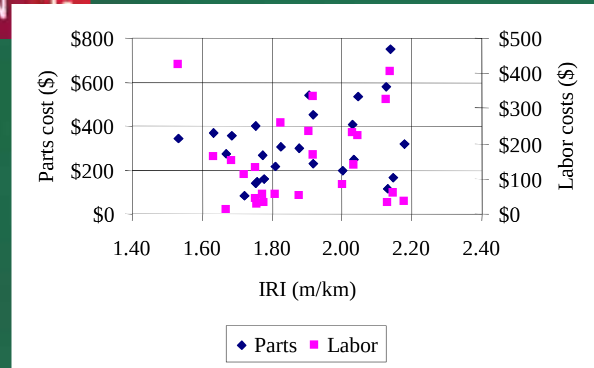
Updating Zaniewski's tables



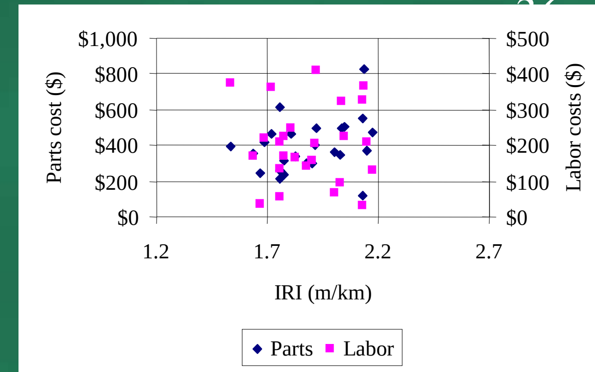
Data Analysis (Empirical approach)

- Repair and maintenance costs from Texas DOT and Michigan DOT
- Extract only repair costs related to damage from vibrations:
  - Underbody inspection
  - Axle repair and replacement
  - Shock absorber replacement

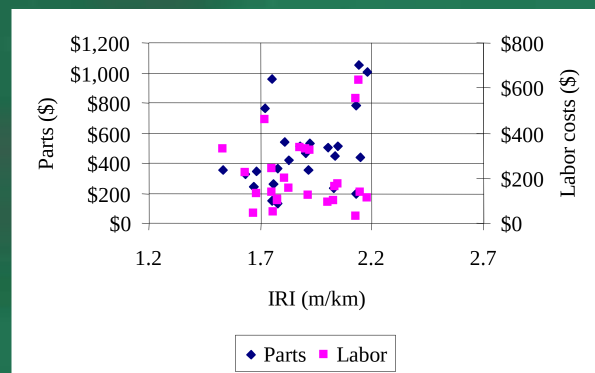
R&M Costs from MDOT



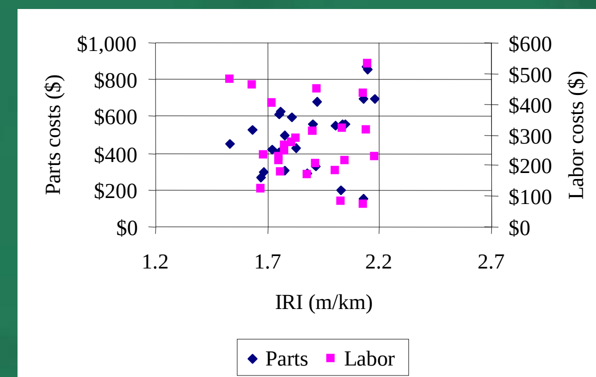
(a) Passenger Car



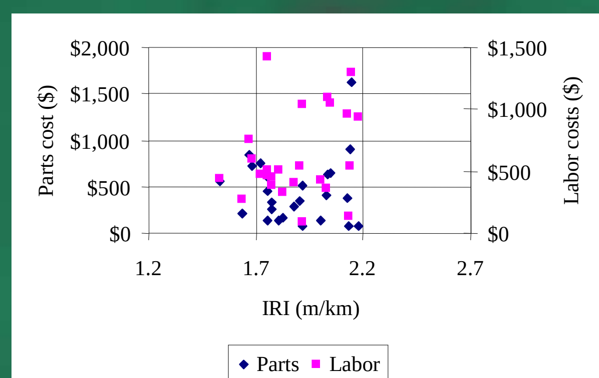
(b) Light Trucks



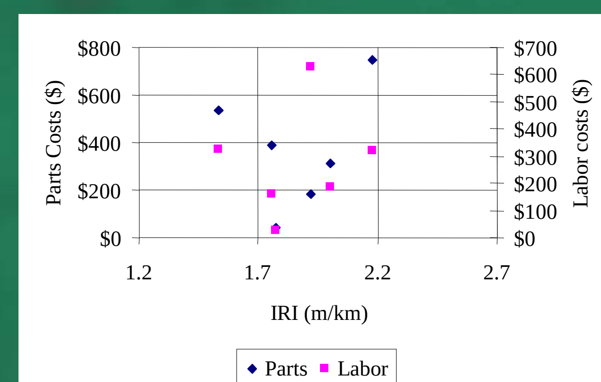
(c) Medium Trucks



(d) Heavy Trucks



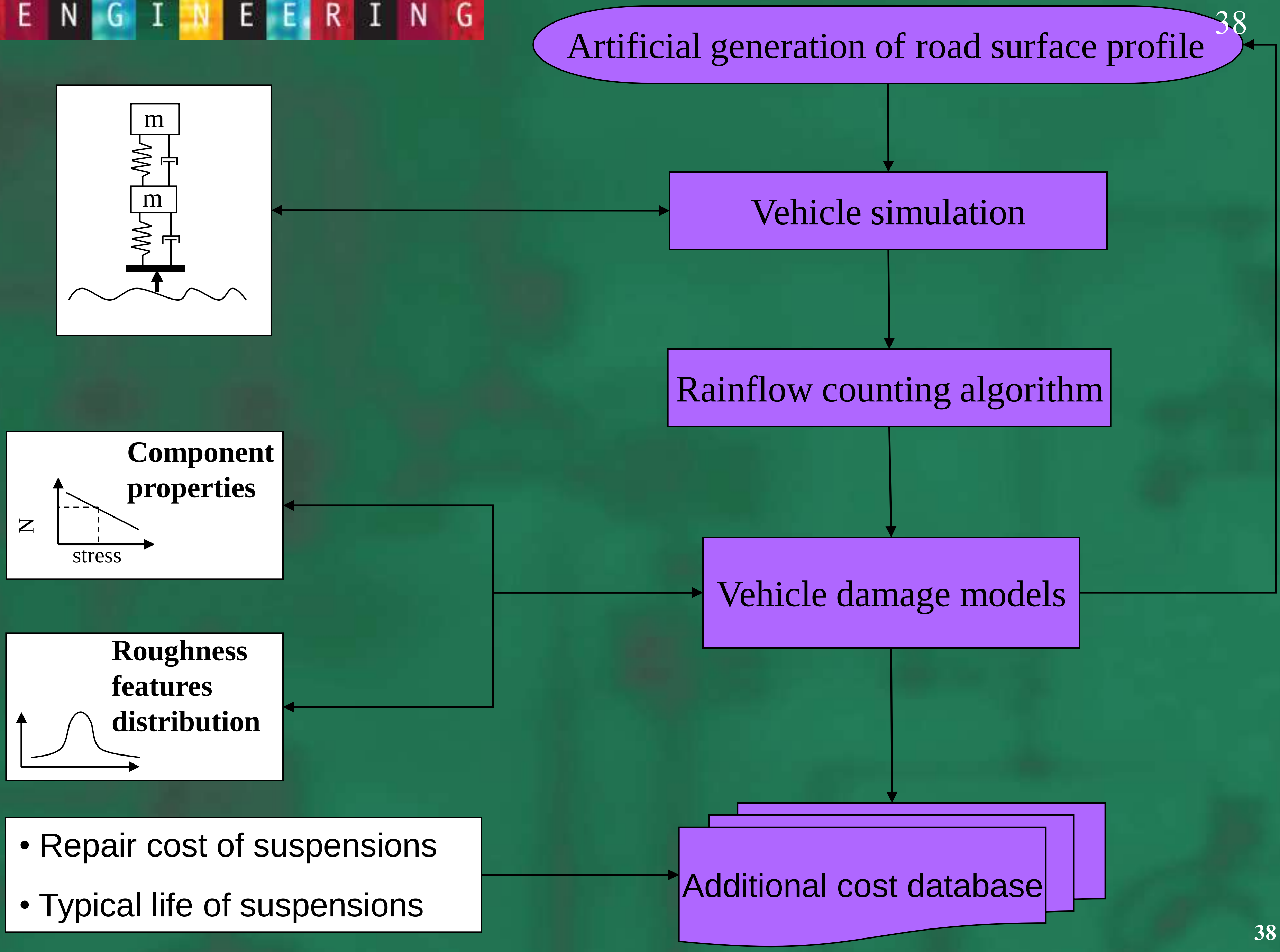
(e) Articulated Trucks



(f) Buses

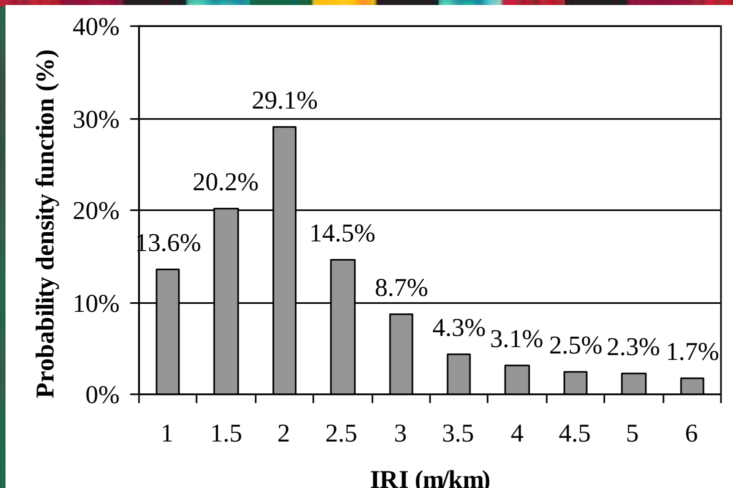
Mechanistic Approach

- A mechanistic-empirical approach was proposed to conduct fatigue damage analysis using vehicle-pavement interaction modeling.


Artificial generation of road surface profile
m
m
Vehicle simulation
Rainflow counting algorithm
Component properties
N
stress
Vehicle damage models
Roughness features distribution
• Repair cost of suspensions
• Typical life of suspensions
Additional cost database

Failure threshold

- User perspective : Replace parts when certain signs of wear become evident.
- Manufacturer lifetime warranty:
  - Truck suspensions : 250,000 miles
  - Car suspensions : 100,000 miles



Multiply the PDF with 250,000 or 100,000 miles

Vehicle miles traveled over each roughness level

Generate 30 Road Profiles for each roughness level

= Damage threshold

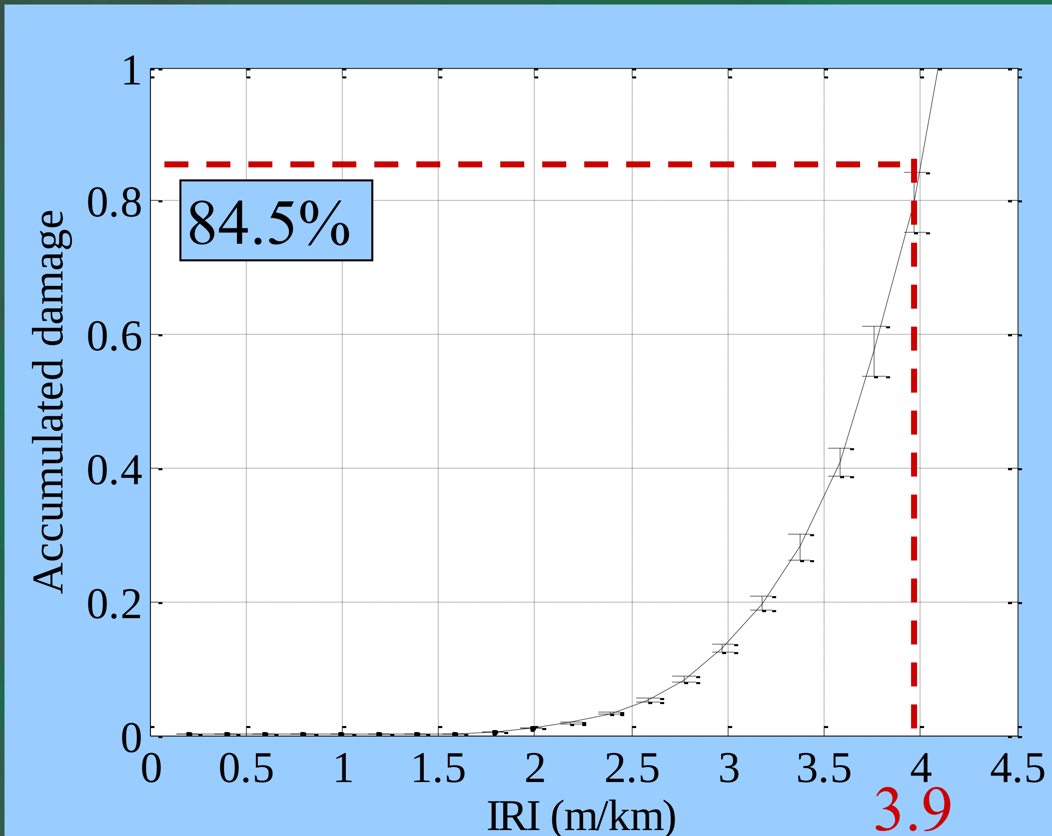
Vehicle simulation damage analysis

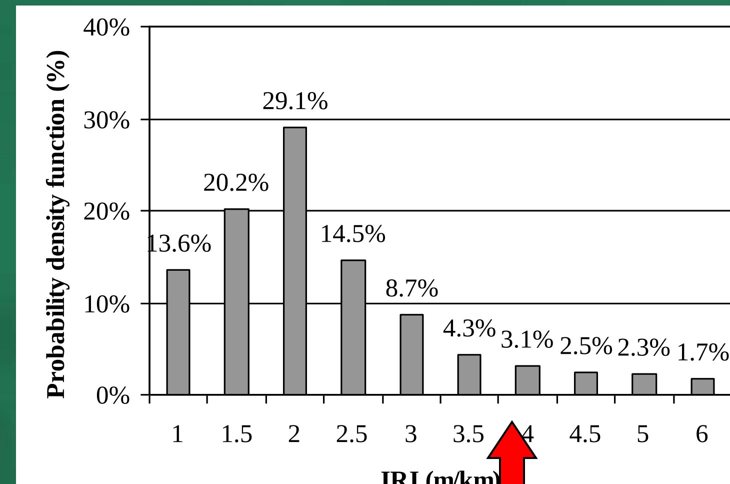
Accumulated damage caused by each roughness level

Failure threshold (Cont'd)

- For cars: 87.3 %
- For trucks: 62.2 %
- Vehicle manufacturers design their vehicles for:
  - Cars: 90th to 95th percentile of roughness
  - Trucks: 80th to 95th percentile of roughness

For cars

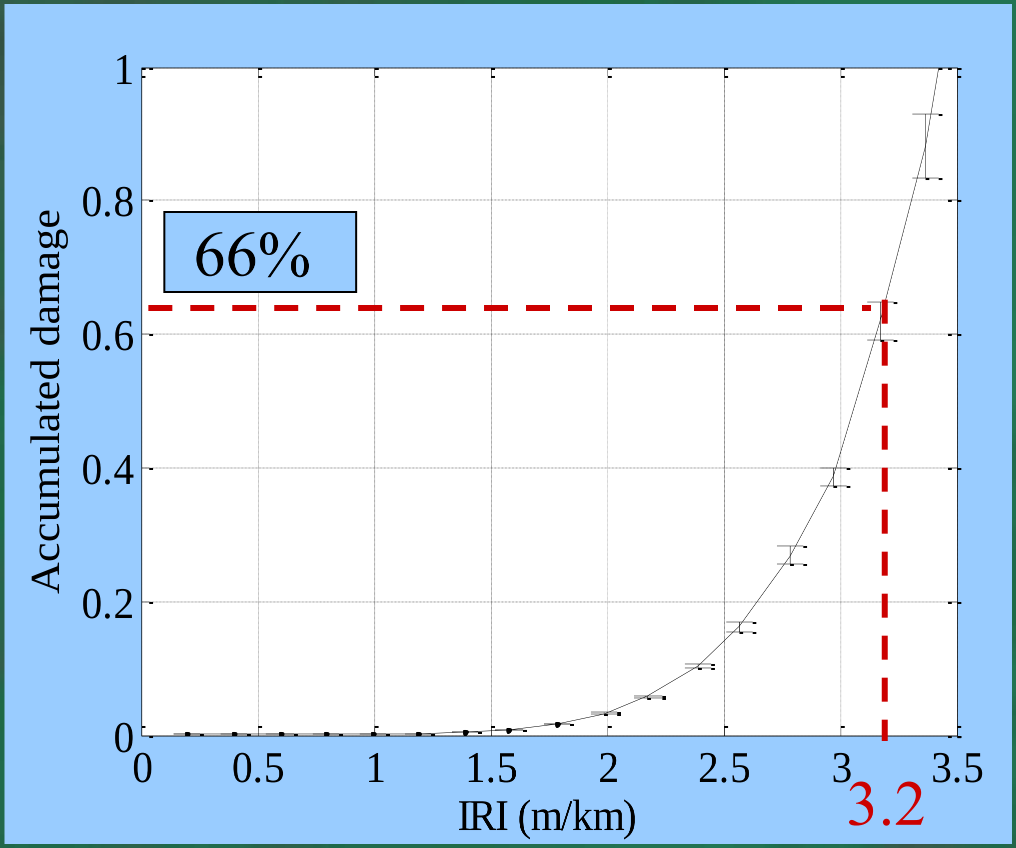


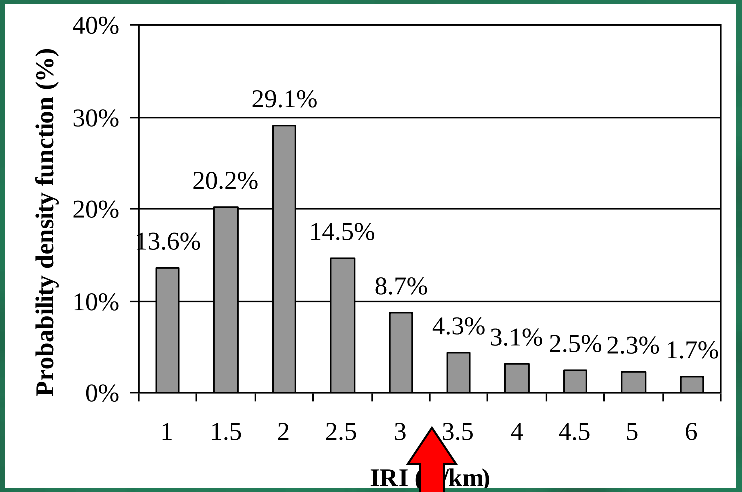


93rd percentile

Car manufacturers design their vehicle for the 90th to 95th percentile of roughness

For trucks



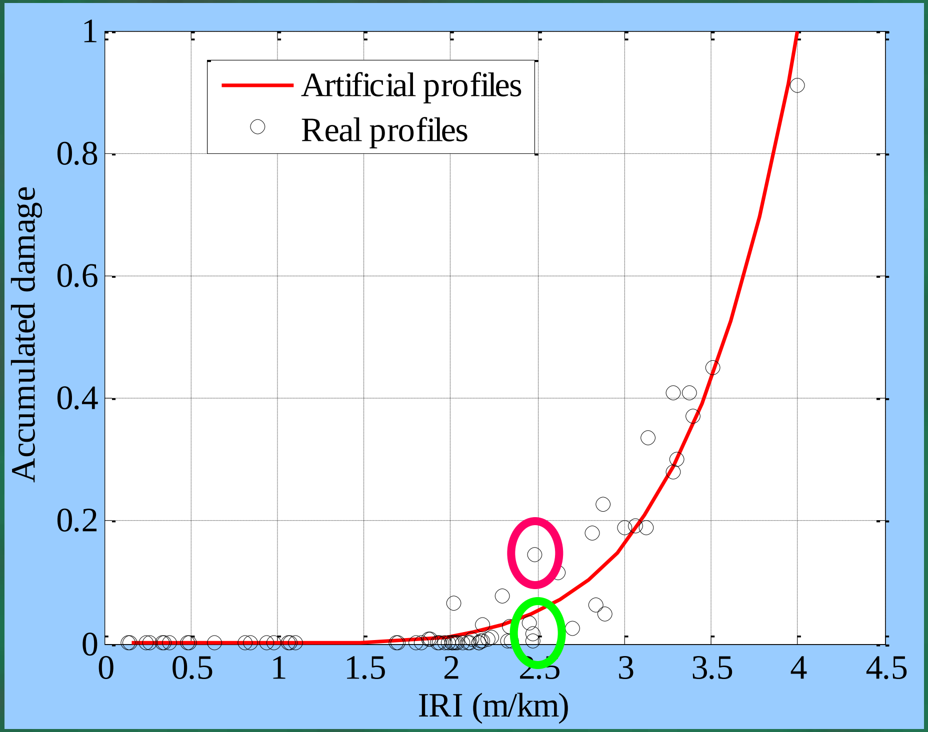


87th percentile

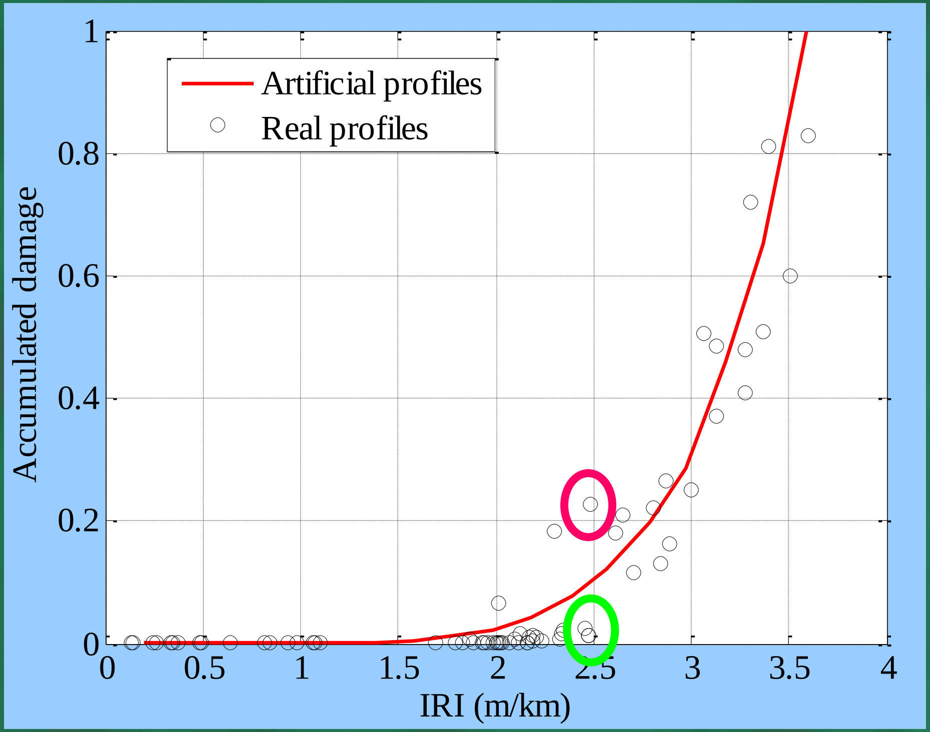
Truck manufacturers design their vehicle for the 80th to 95th percentile of roughness

Accumulated damage using actual profiles from in-service pavements

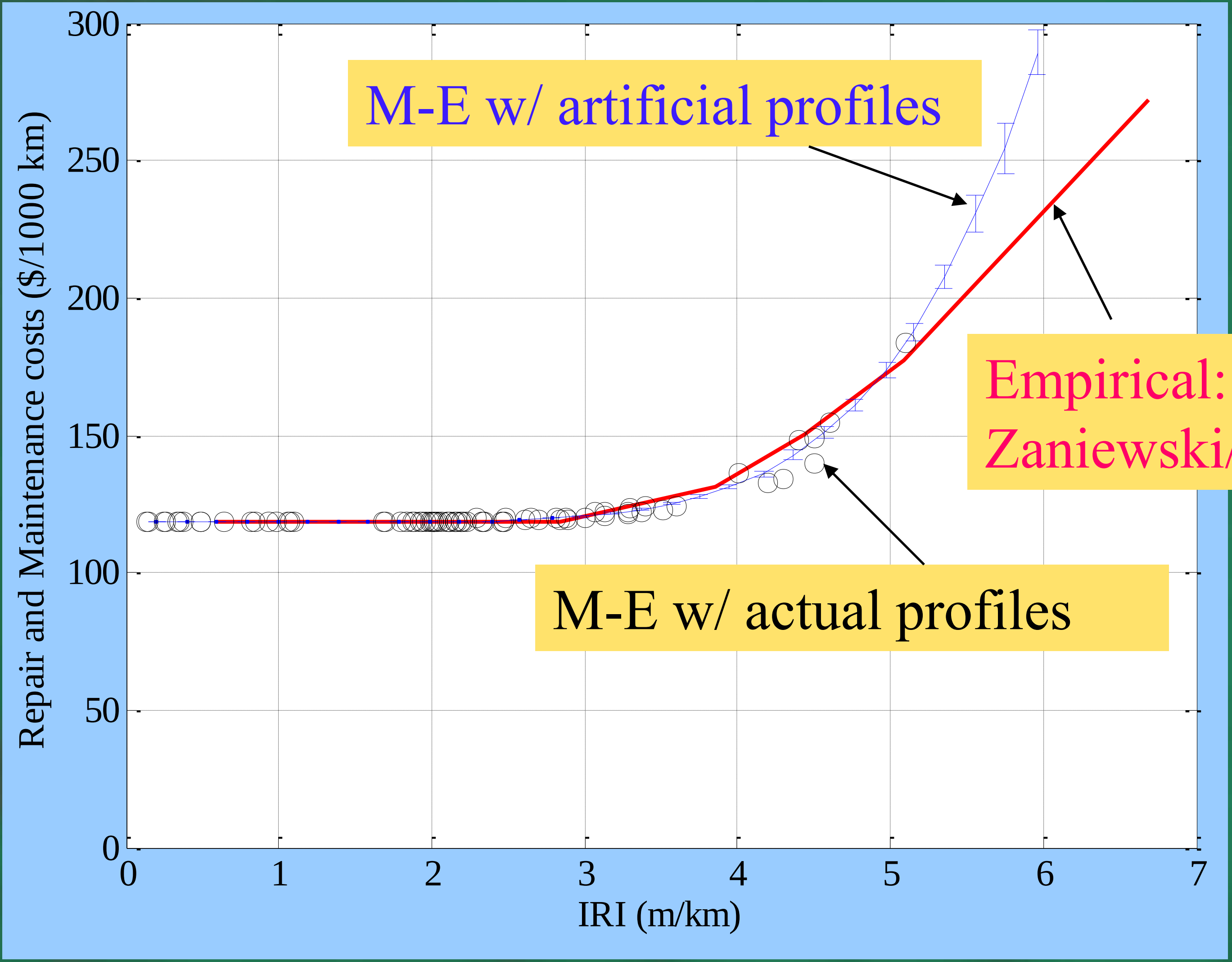
Cars



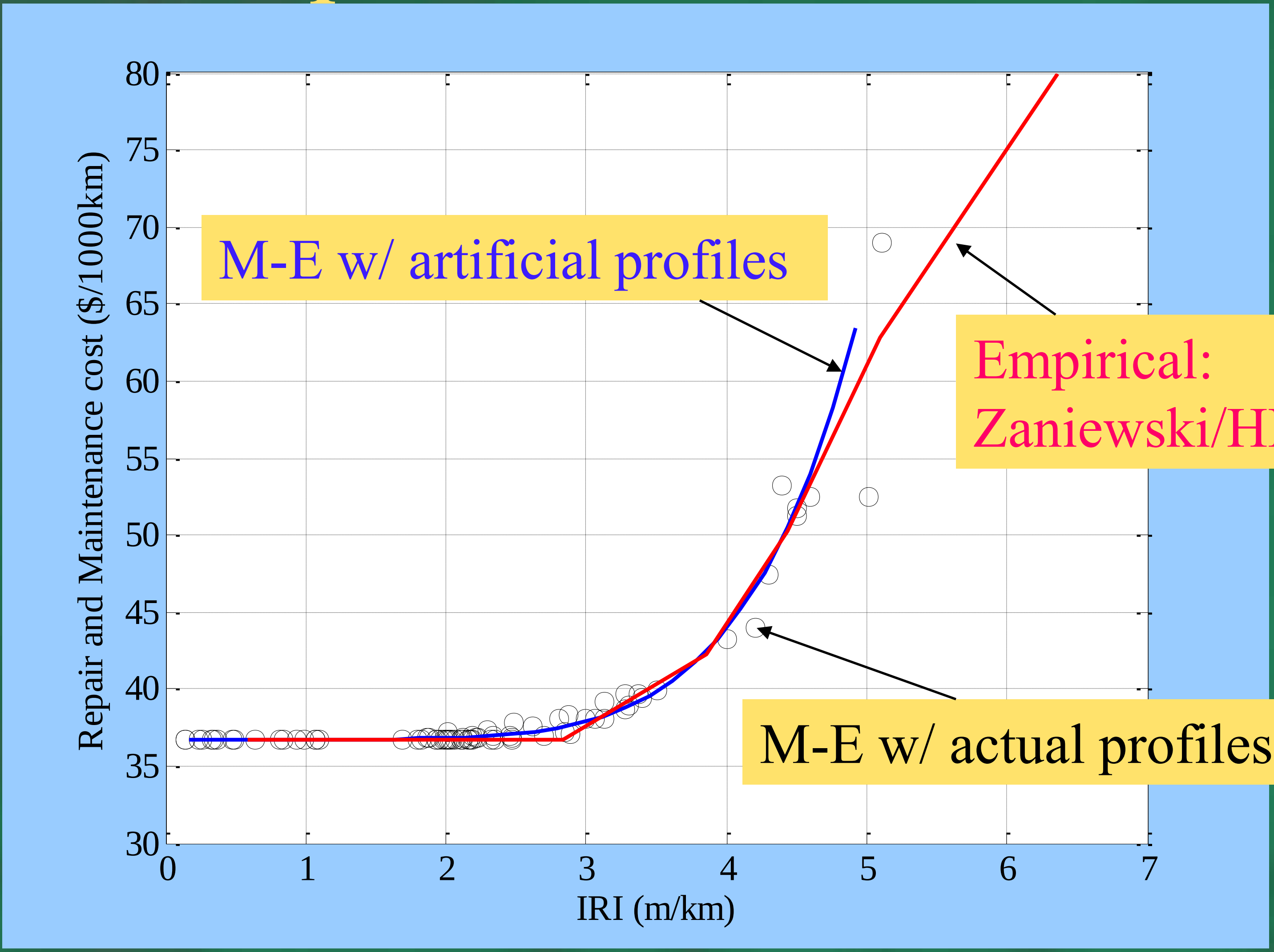
Trucks



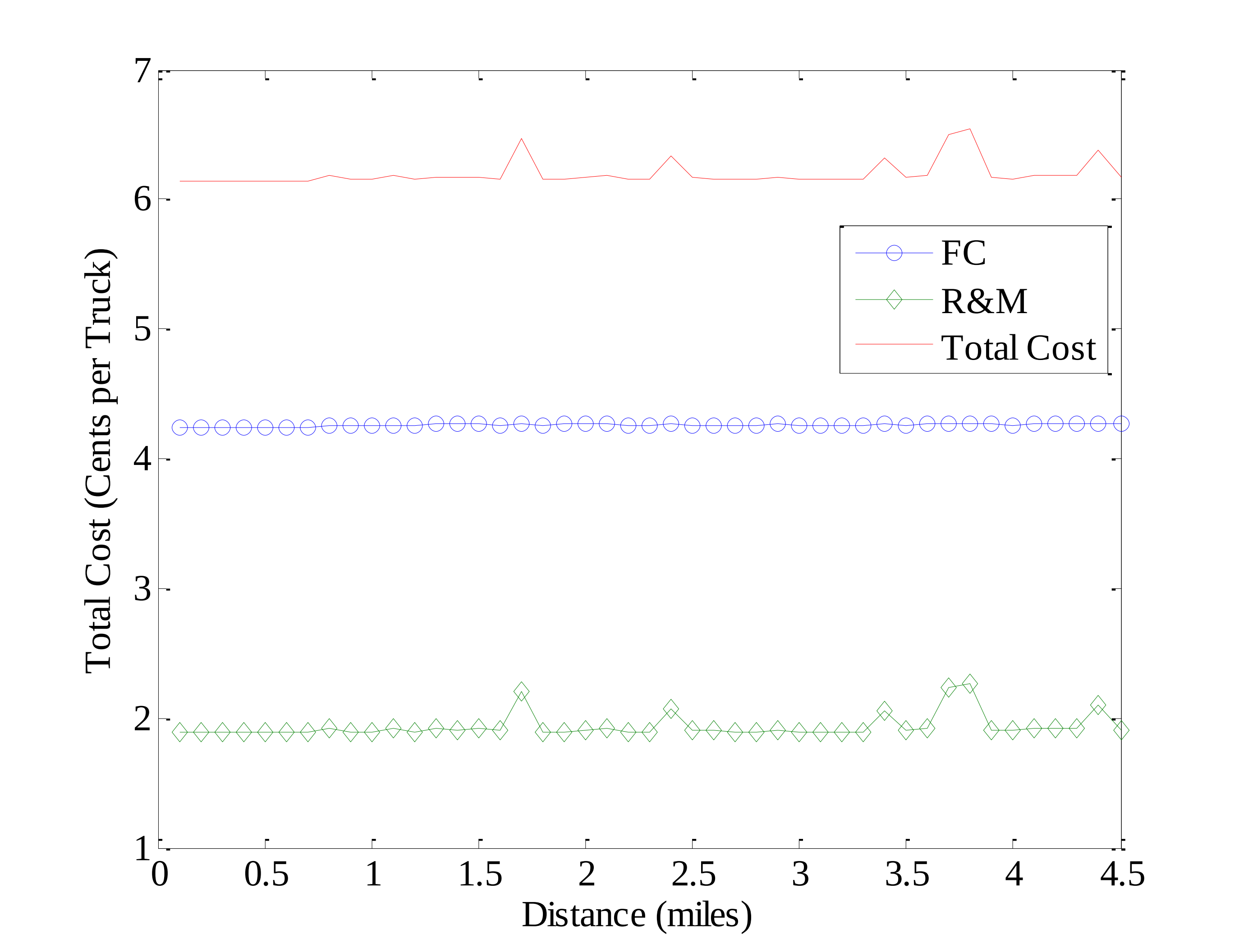
Empirical versus mechanistic predictions: Trucks



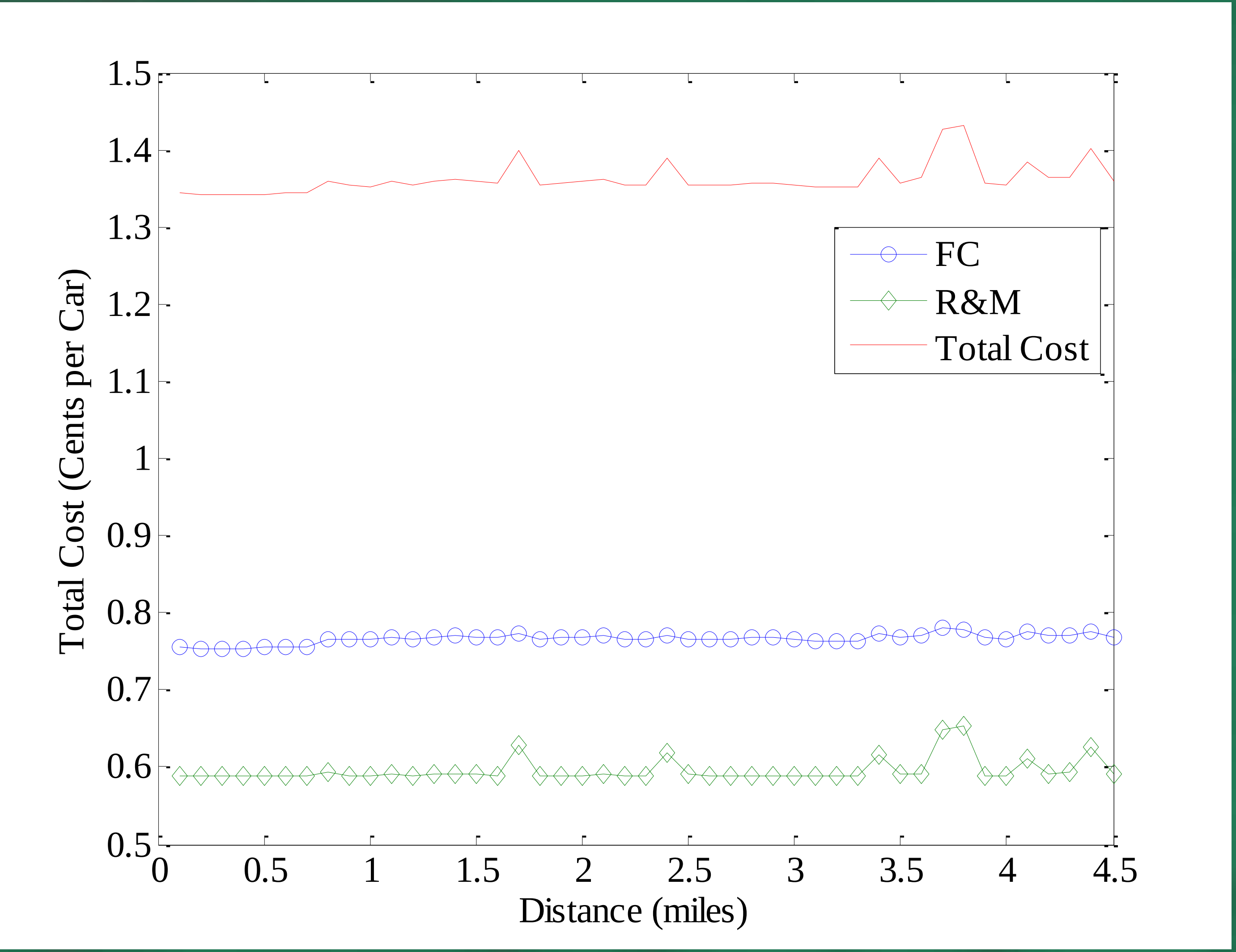
Empirical versus mechanistic predictions: Cars



Example: VOC for Trucks caused by I69 condition



Example: VOC for Cars caused by I69 condition




Any Questions ?