Assessing Pavement Roughness In Urban Environments

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Outline

- Introduction
  - Roughness Impact Factors
  - Connected Vehicles
- Methods
  - The International Roughness Index (IRI)
  - The Road Impact Factor (RIF) Transform
- Field Experiments
- Results
- Conclusions

Current Method and Tradeoff

Our Goal

Visuals
(Expensive to Scale)

Source: FHWA (2012)

Profilographs
(Less Automated)

Source: Caltrans (2014)

Inertial Profilers
(Difficult Beyond Highways)

Source: Fugro Roadware, 2015

Accuracy

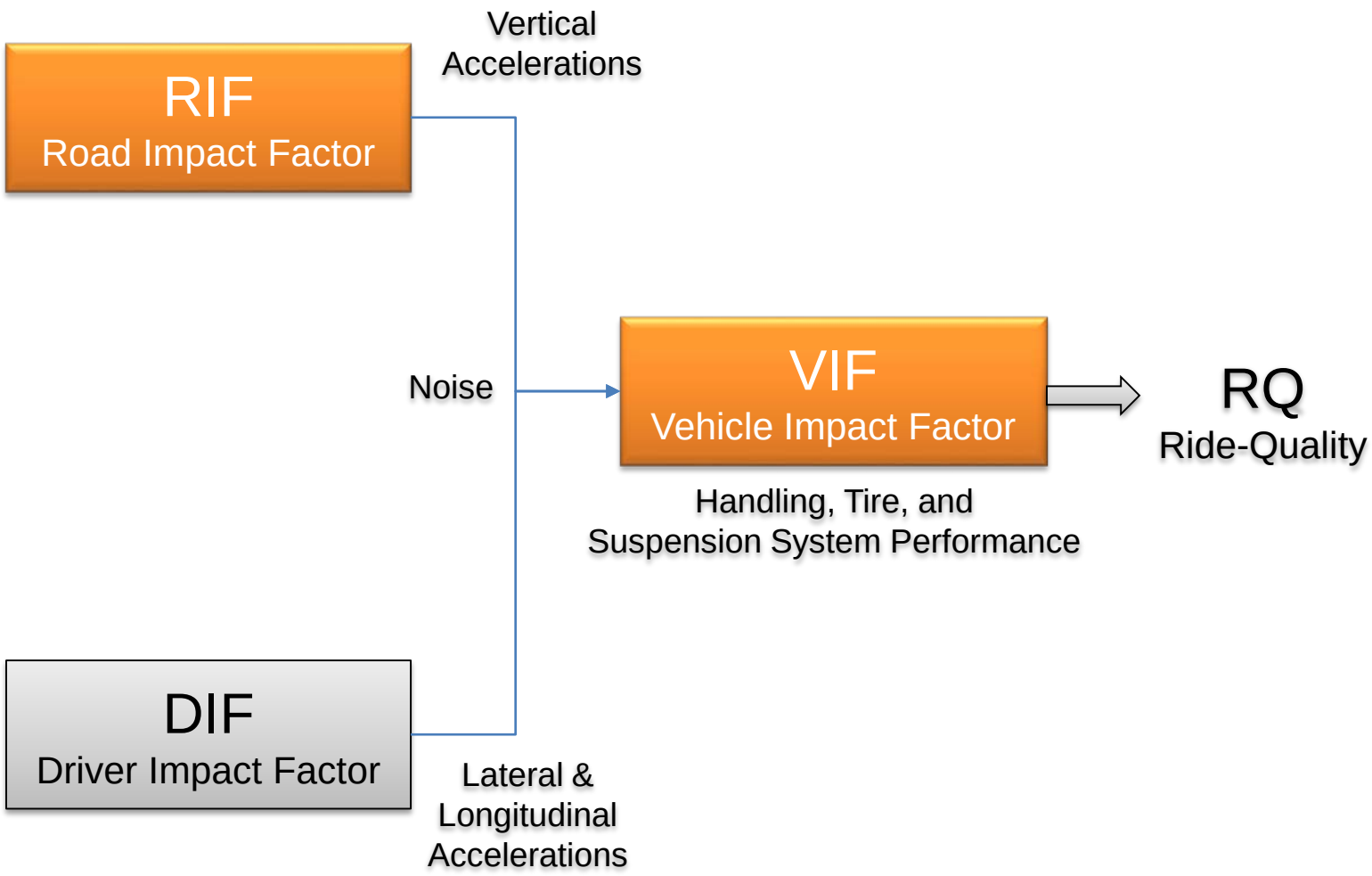
Cost

The Connected Vehicle Opportunity

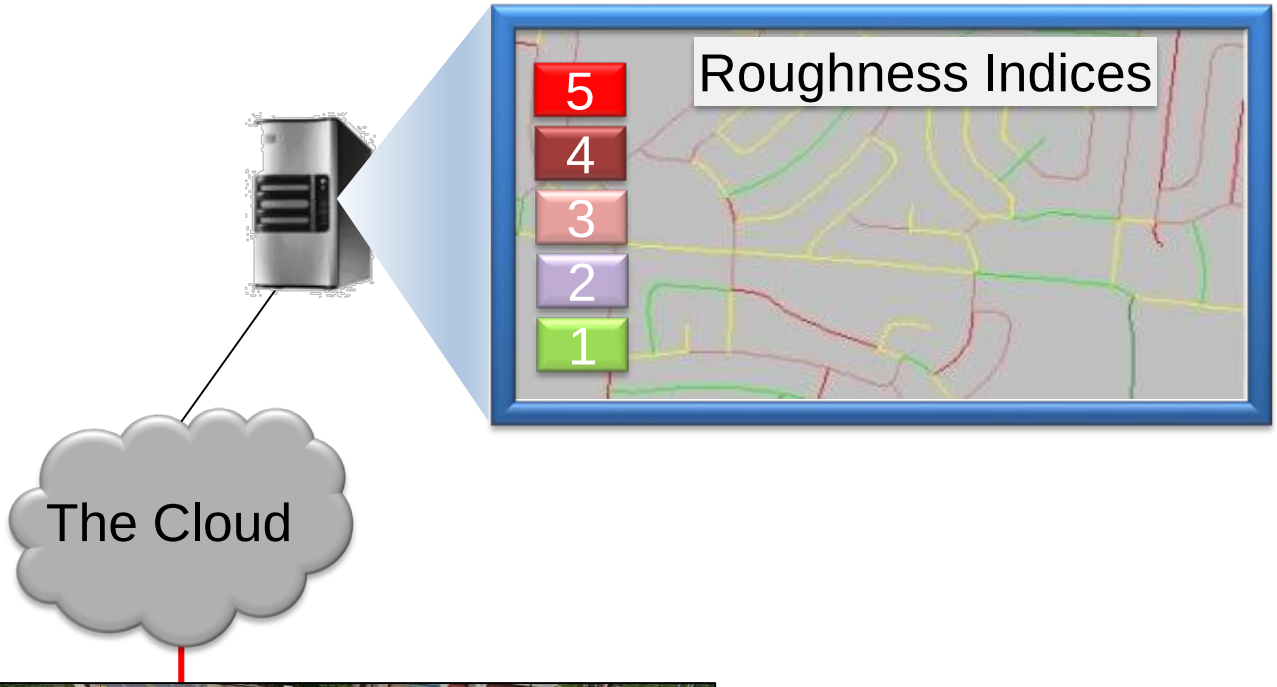
Source: The USDOT (2015)

Can we use Connected Vehicles to characterize ride quality?

What is Ride Quality?



The Connected Vehicle Approach

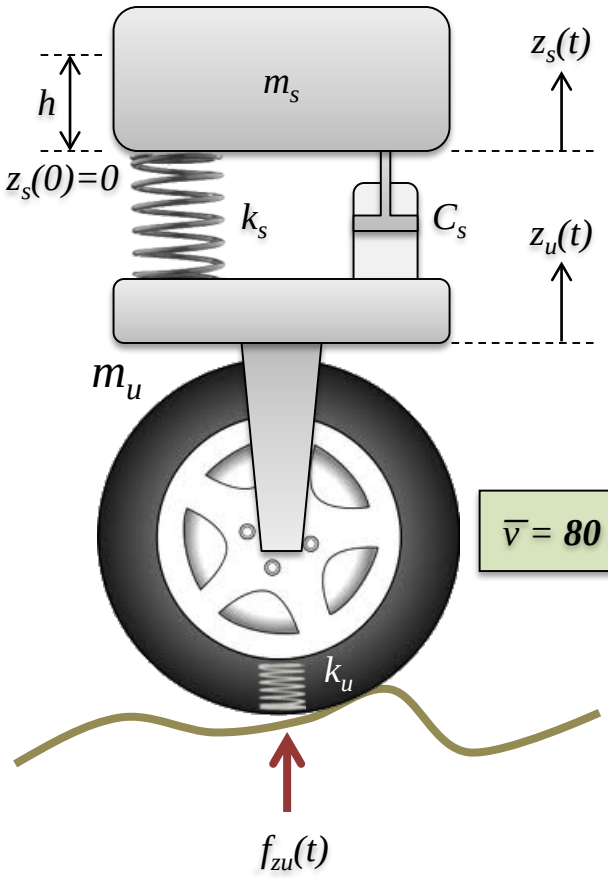


Accelerometers

- Airbag control
- Inertial navigation
- Stability control
- Fault diagnosis

GPS Receivers

Review of the International Roughness Index (IRI)



$\overline{v}$ = **80** km/h

The Golden Car Parameters

Parameter	Value	Unit
k_s/m_s	63.3	S^{-2}
k_u/m_s	653	S^{-2}
C_s/m_s	6	S^{-1}
m_u/m_s	0.15	-

80 km/h

Solve these with the Profile Input

$$\ddot{z}_s(t)+\frac{c_s}{m_s}\dot{z}_s(t)+\frac{k_s}{m_s}z_s(t)=\frac{1}{m_s}z_u(t)$$ **Sprung-mass (Body Bounce)**

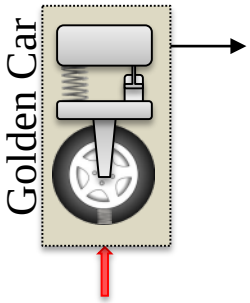
$$\ddot{z}_u(t)+\frac{c_u}{m_u}\dot{z}_u(t)+\frac{k_u}{m_u}z_u(t)=\frac{1}{m_u}f_{zu}(t)$$ **Unsprung-mass (Axle Bounce)**

The IRI Definition

$$IRI=\frac{1}{L}\int_0^{L/\overline{v}}\left|\dot{z}_s(t)-\dot{z}_u(t)\right|dt \qquad (19)$$

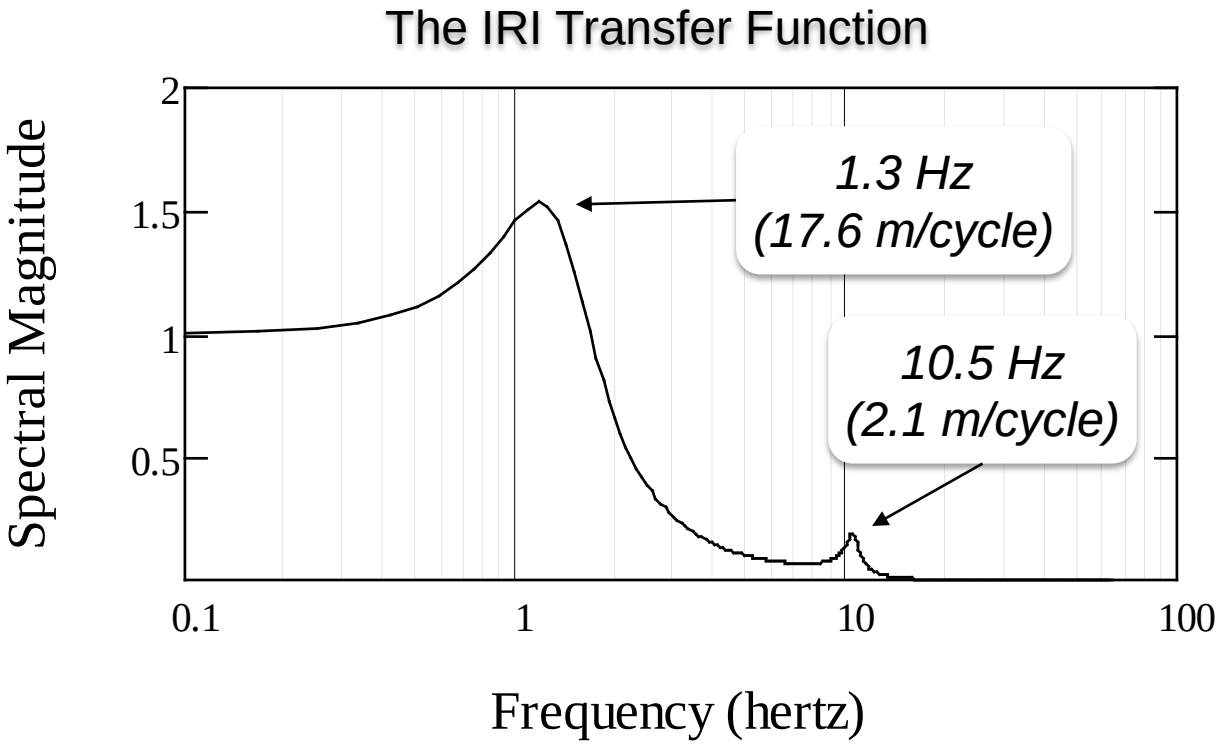
The IRI assumes that the Golden Car models the typical vehicle response.

The IRI Wavelength Sensitivity



Transfer Function

Profile Wavelength @ 80 km/h



The Golden Car accentuates roughness with spatial wavelengths of 2 m and 18 m.

Profile wavelengths translate to different frequencies at different speeds.

The actual transfer function of a real vehicle differs from the Golden Car.

How does the RIF Transform work?

Time	Latitude	Longitude	Speed	Pitch	Roll	Yaw	Gx	Gy	Gz
1866.466	30.445584	-97.594473	19.30	80.82	33.46	-75.81	0.152	-1.005	-0.137
1870.249	30.445584	-97.594473	19.30	80.82	33.46	-75.81	0.087	-0.919	-0.104
1875.429	30.445584	-97.594473	19.30	80.82	33.46	-75.81	0.028	-0.855	-0.143
1889.969	30.445416	-97.594427	19.33	80.87	33.38	-75.78	-0.009	-1.146	-0.182
1898.306	30.445416	-97.594427	19.33	80.96	34.01	-76.39	0.031	-0.948	-0.042
1902.281	30.445416	-97.594427	19.33	80.96	34.01	-76.39	0.190	-1.058	-0.093
1909.142	30.445416	-97.594427	19.33	80.88	34.01	-76.35	0.222	-1.041	-0.170
1912.815	30.445416	-97.594427	19.33	80.88	34.01	-76.35	0.090	-0.840	-0.172
1919.346	30.445416	-97.594427	19.33	80.88	34.01	-76.35	0.033	-1.029	-0.243
1924.427	30.445416	-97.594427	19.33	80.77	33.32	-75.68	0.007	-1.068	-0.063

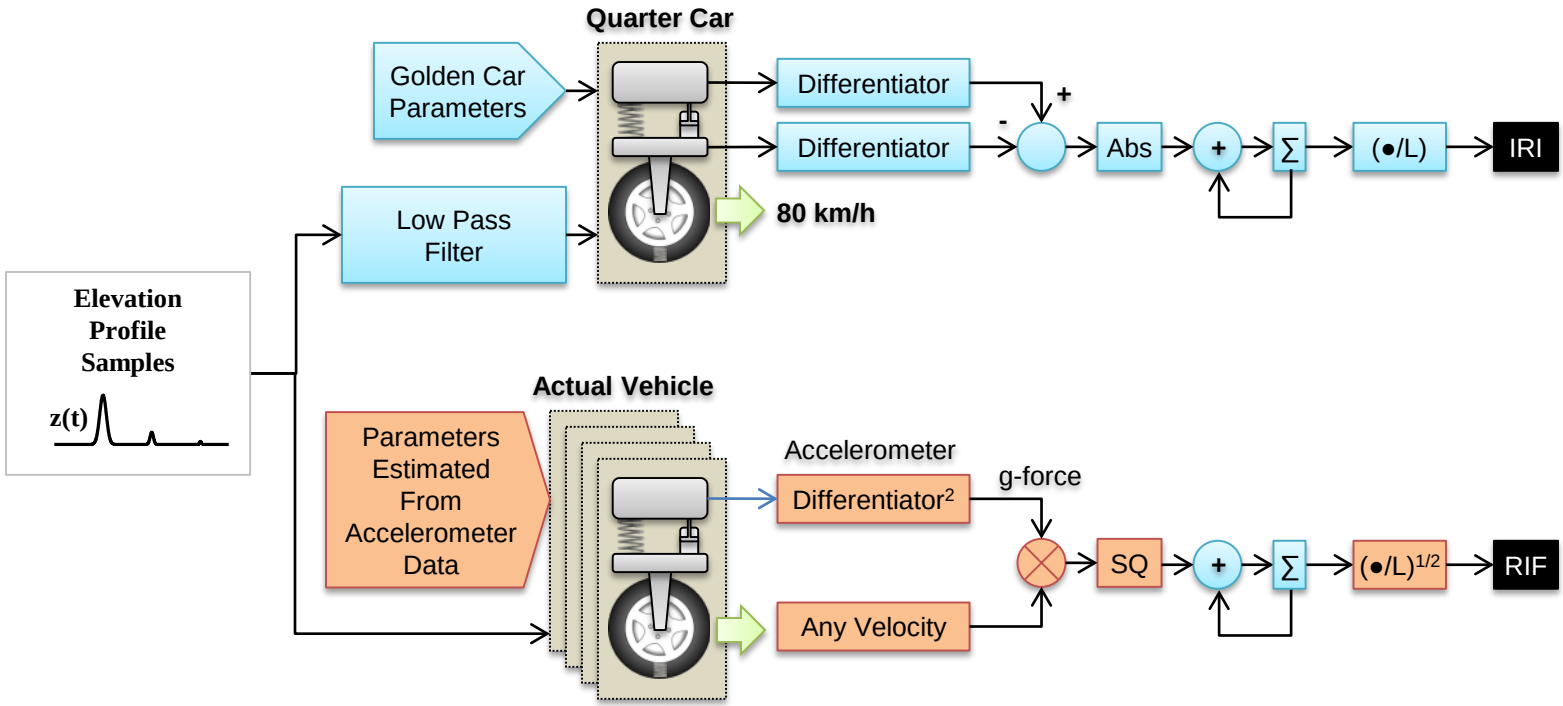
Path Distance Increment
$\Delta L, N, \delta t$

Resultant Vertical Acceleration
$g_{z[n]}$

$$R_{\bar{v}}^{L} = \sqrt{\frac{\delta t}{\Delta L}\sum_{n=0}^{N}\left[g_{z[n]}v_n\right]^2}$$

1) Establish a geo-fence along the road to mark the analysis start position
2) Interpolate the path distance based on the time and velocity instants
3) Accumulate the distance to the desire length to mark the stop position
4) Produce an orientation independent resultant vertical acceleration
5) Compute the RIF per unit of distance resolution

How are the RIF and the IRI related?



The RIF and the IRI are directly proportional at a given speed.

The IRI is **simulated** from a **fixed** quarter-car at a **fixed** speed.

The RIF is computed from an **actual** vehicle response at **any** speed.

The Speed Independent Transform

TWIT

$$\Psi_k(P_j) = \frac{\sum_{w=1}^{N_k} \overline{R}^{L}_{\bar{v}[w]} \times N^{P_j}_{\bar{v}[w]}}{\sum_{w=1}^{N_k} N^{P_j}_{\bar{v}[w]}} \quad (31)$$

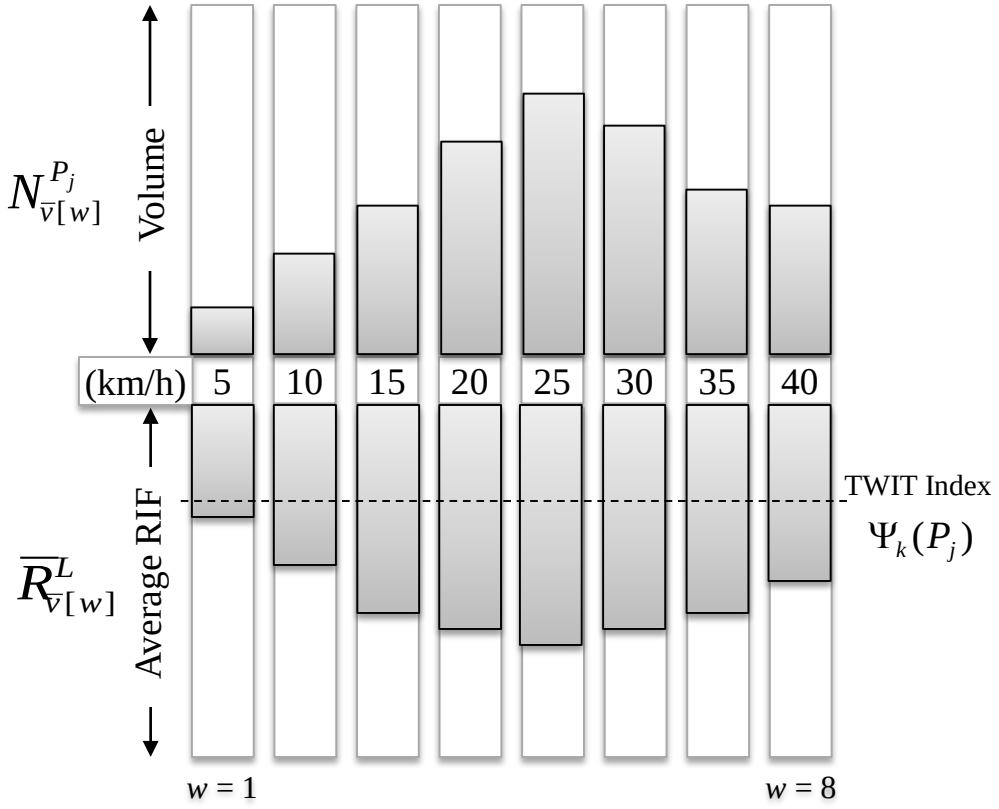
N_k = Total traversal volume for segment k

P_j = Time period j $\quad$ w = Speed band

Database Filters (Decisions)

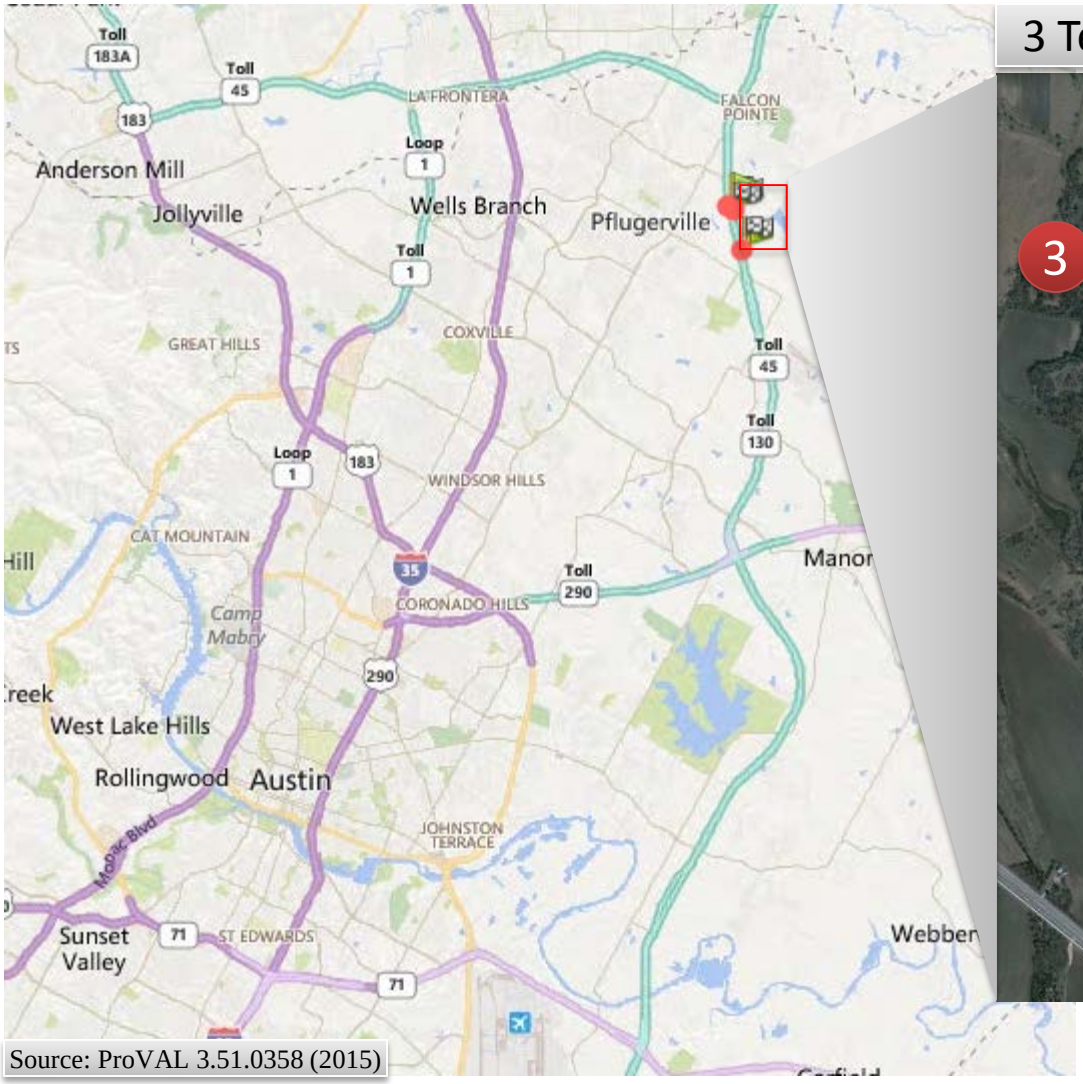
- Road segment (regions)
- Data range (exclude rain/snow)
- Hour range (peak vs. off-hours)
- Temperature (seasons)
- Speed band (speed limit $\pm\Delta$)
- Speed band width ($\pm\Delta$ tradeoff)
- Vehicle type (popular sedans)

Time-Wavelength-Intensity Transform



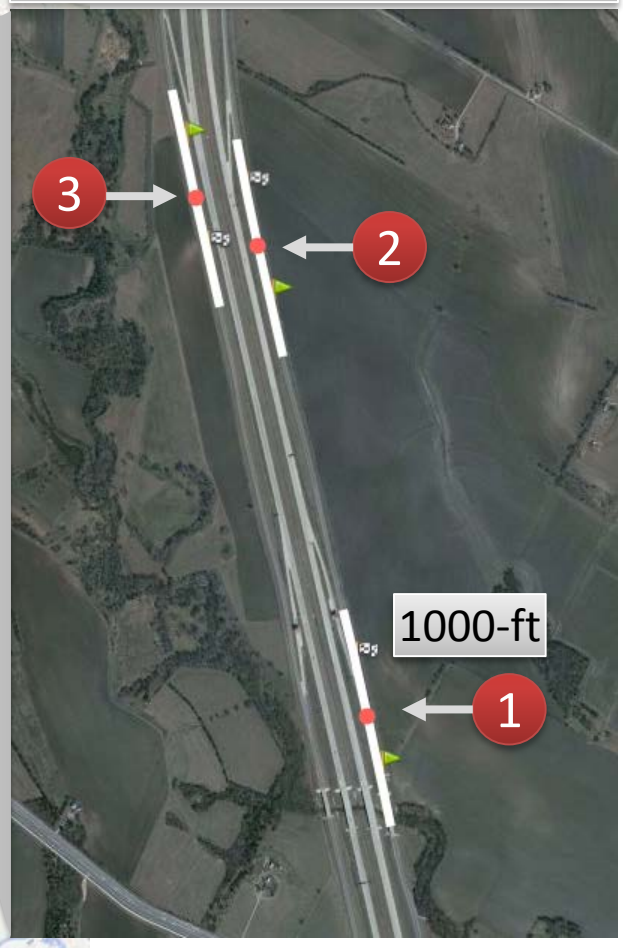
The TWIT reports the average roughness experienced at all speeds.

Test Site Location

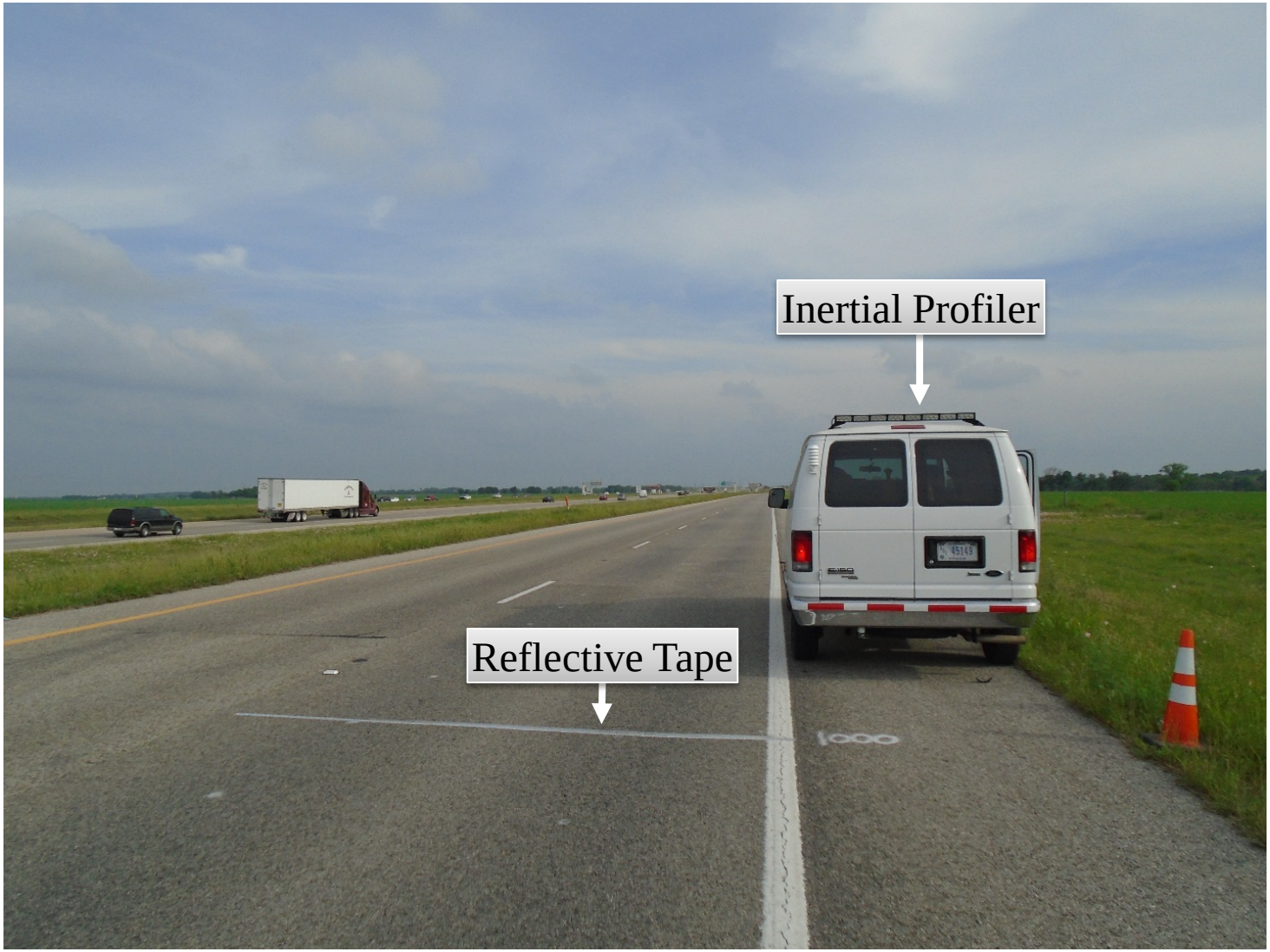


Source: ProVAL 3.51.0358 (2015)

3 Test Sites: TX 130 Frontage



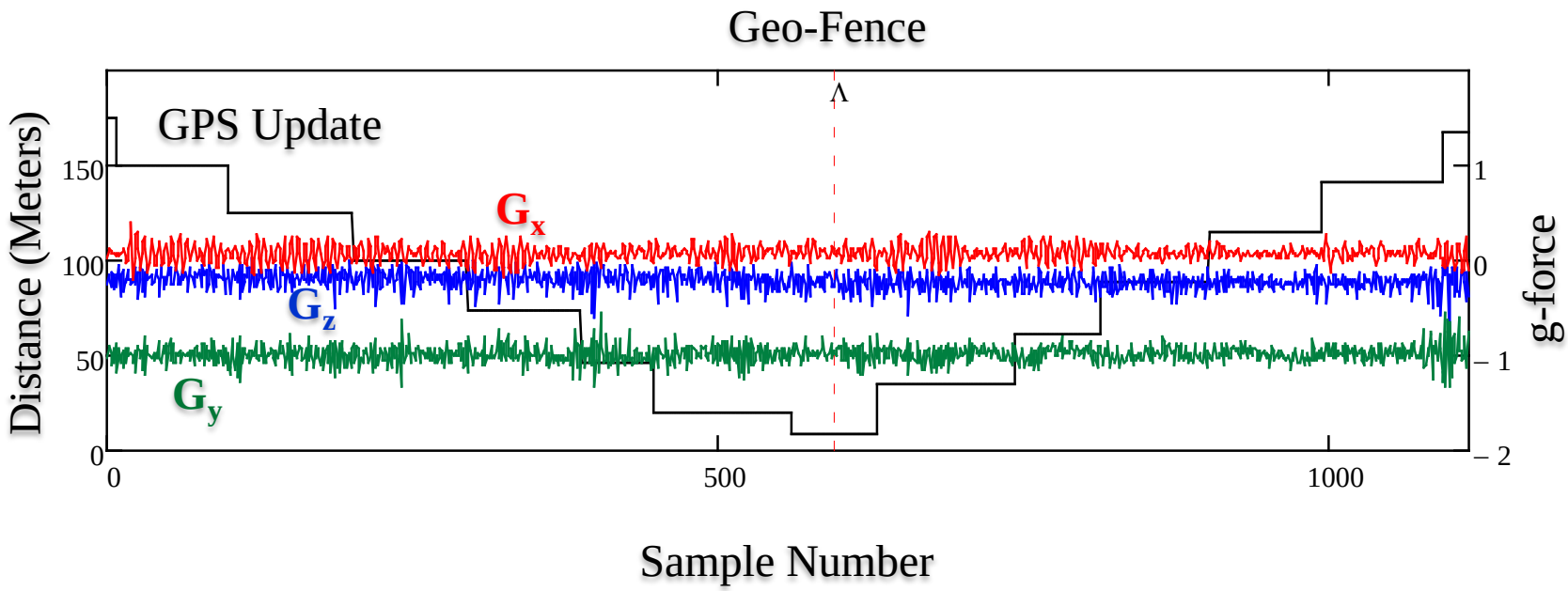
Site View and Inertial Profiler



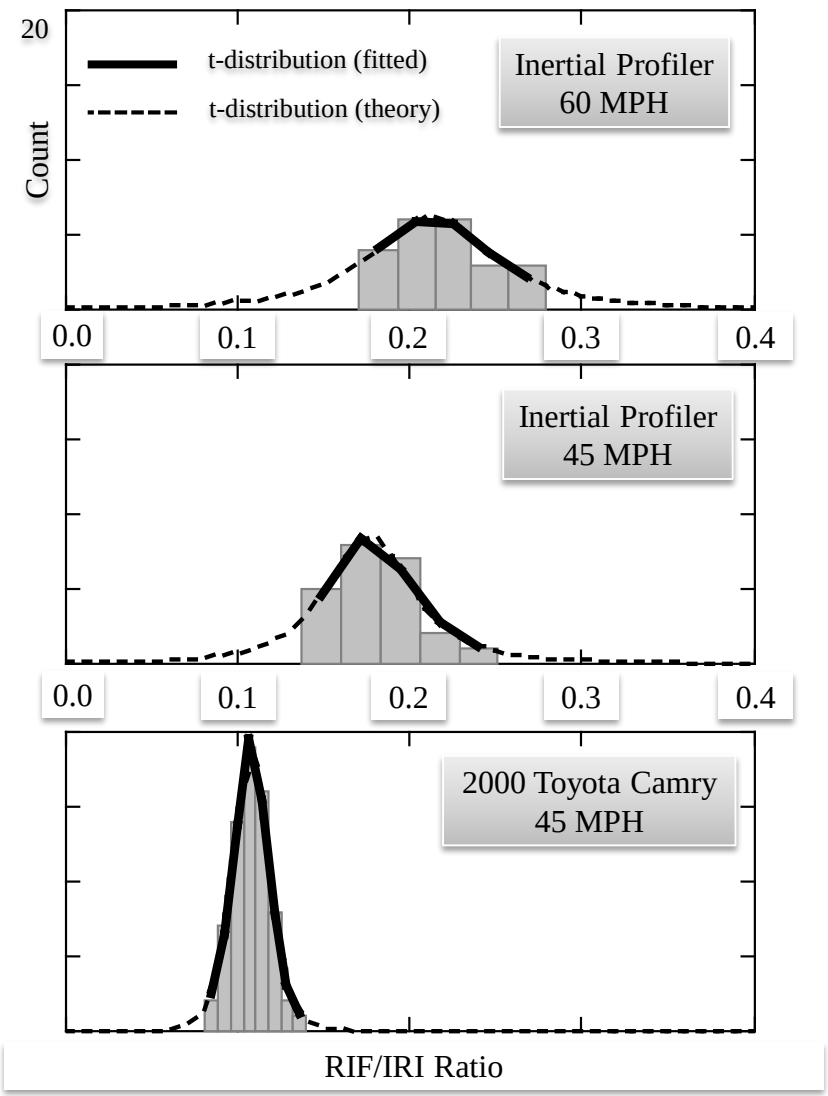
Site View and 2000 Toyota Camry

Smartphone Installation

Smartphone Data and Geo-Fence Trigger



Statistics of the RIF/IRI Proportionality



Mean = 0.218
STD = 0.030
N = 22
MOE_{95} = 6.1%
χ^2_t = 77.4%

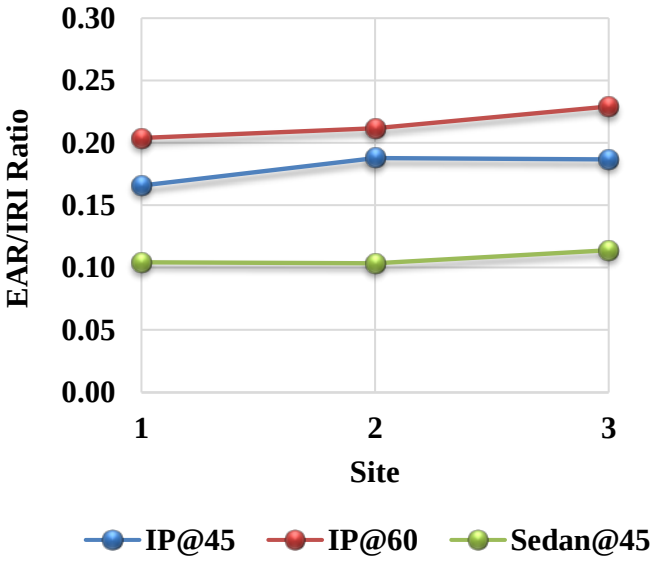
Mean = 0.181
STD = 0.025
N = 23
MOE_{95} = 5.9%
χ^2_t = 81.5%

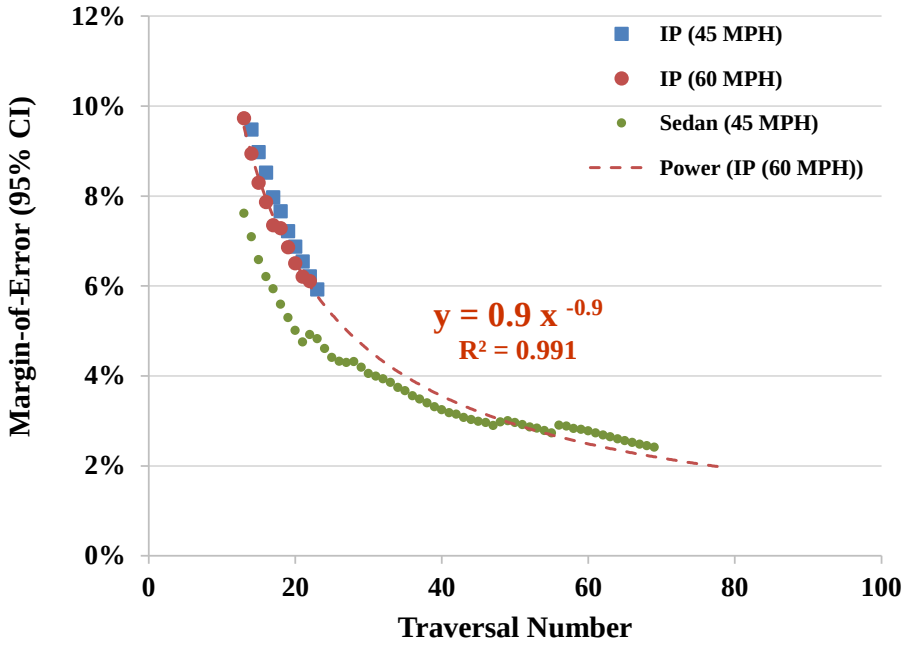
Mean = 0.107
STD = 0.011
N = 69
MOE_{95} = 2.4%
χ^2_t = 98.6%

Key Points

- The Student t-distribution is appropriate for sample sizes fewer than 30
- Chi-squared testing cannot reject the hypothesis that the data fits the Student t-distribution (>> 5% significance)
- The margin-of-error approaches 2% with the higher traversal volume from the sedan
- The RIF/IRI ratios reflect the differences in traversal speeds (wavelength sensitivity) and suspension responses

Summary of Results





Key points

- Higher RIF-indices at higher speeds is consistent with the theory
- The VIF of the sedan produces lower RIF-indices then the Van
- The RIF/IRI ratios change slightly across test site
- They slight change in RIF/IRI ratios generally agree across test sites
- The MOE_{95} approaches 2% as the traversal volume approaches 80

Summary and Conclusions

- The Connected Vehicle approach characterizes ride quality with high accuracy and precision
  - For a given vehicle type
  - For traversal volume beyond 80
  - Will require greater traversal volumes for mixed vehicle populations
  - Convergence is guaranteed vis-à-vis the law of large numbers
- The technology is practice ready
  - Use smartphones now to collect the data
  - Implement the RIF-transform in a GIS platform