Investigation of Pavement Maintenance Applications of Connected Vehicle Systems

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Methodology Development and Testing

Objectives

- Investigate the potential for typical sensors in passenger cars to provide probe data useful for monitoring pavement quality
- Estimate International Roughness Index
- Locate and identify potential potholes along roadway
- Develop simple easy to implement algorithms

Motivation

- Requires specialized profiling equipment
  - Typically laser scanners
- International Roughness Index is calculated based on road profile
- Currently accurate roughness measurements are taken fairly infrequently

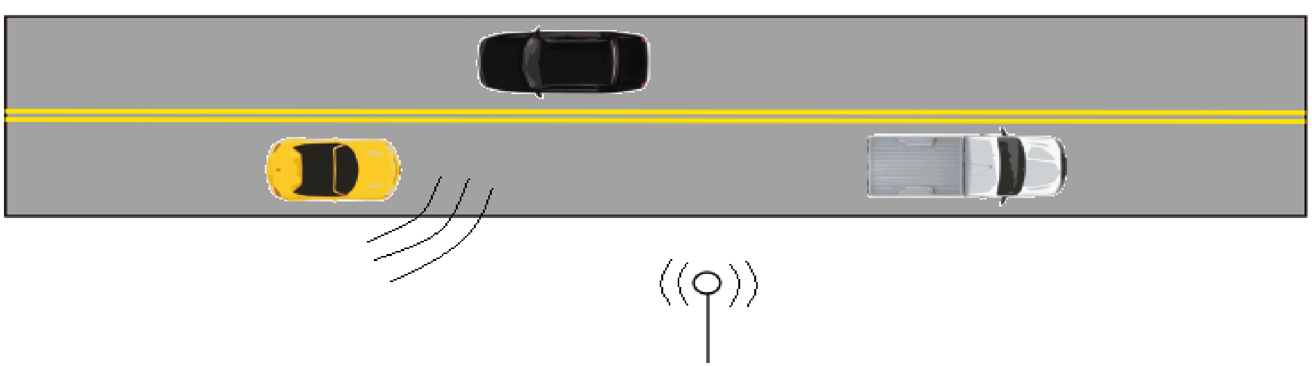
Motivation

- Having estimates of the IRI for the roadways can help DOTs better leverage resources
  - Sending crews to measure IRI based on the current estimates
  - Have knowledge of pothole locations
- More frequent data can better establish trends
- Save time and money by utilizing vehicle information

Motivation

How can Connected Vehicles Help?

- ➢ Vehicles can pass their sensor information to a station
    - ❑ The road roughness changes very slowly over time
    - ❑ The roughness estimation will be more robust with more traffic
- ➢ On board vehicle storing and processing

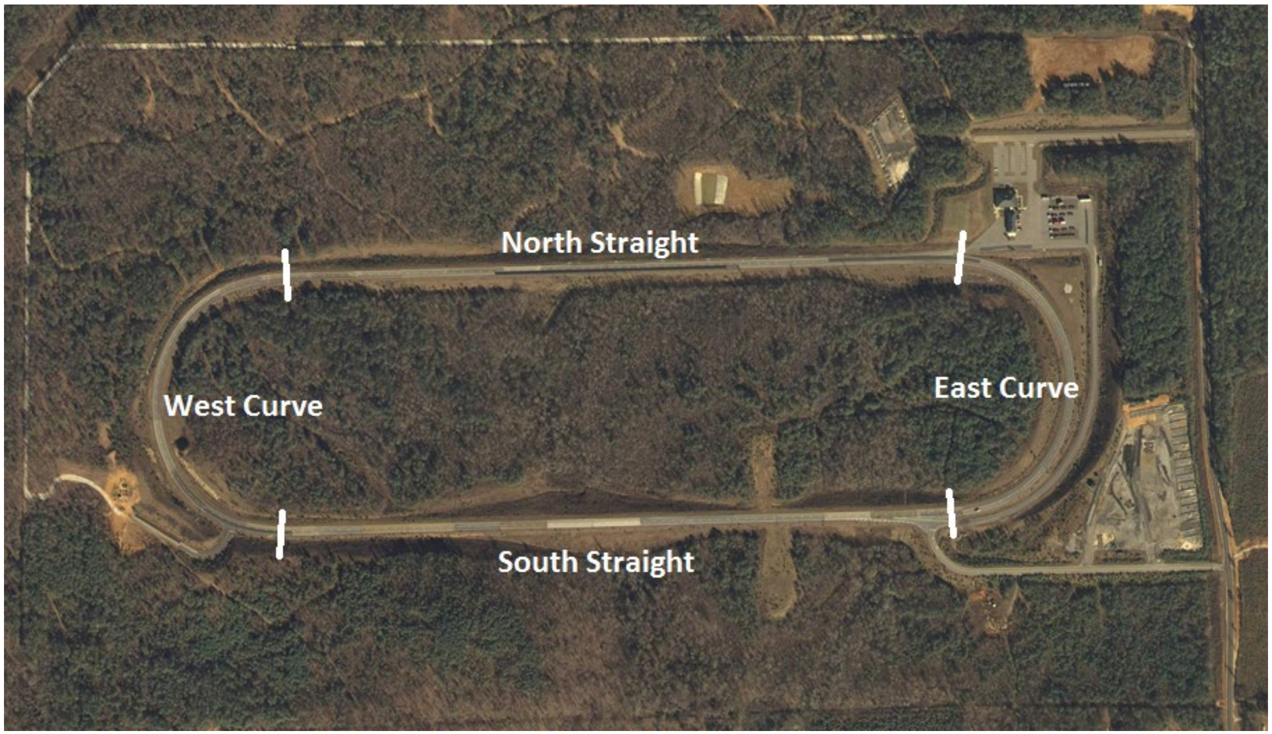


Required Information

- Vehicle Information
  - Mass, suspension parameters
  - Make and model – pull from database
  - Privacy
- Sensor Information
  - Vertical accelerometer – used for roll over detection
  - Pitch rate gyroscope – uncommon in production vehicles
  - Roll rate gyroscope – used for roll over detection
  - Suspension Deflection Sensors – active suspensions

Test Facilities

National Center for Asphalt Technology Test Track



1.7 Mile Oval Track

Test Facilities

- Track has pavement test sections from across the country
- A Lifetime of pavement wear is compressed into a 2-year period

Track equipped with DSRC under FHWA Exploratory Advanced Research project examining positioning in GPS-degraded environments

Testing Equipment

2007 Infiniti G35

Road Profiling Van

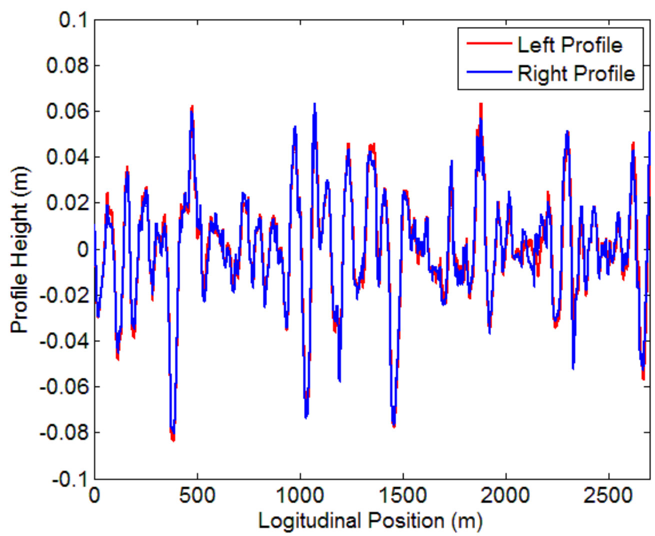
Novatel PropakV3 GPS Receiver

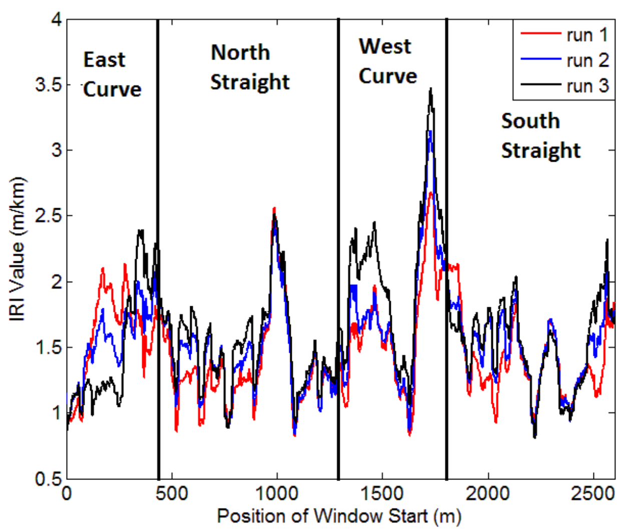
Crossbow440 Inertial Measurement Unit

Celesco Linear Potentiometers

Data Collection

- **Track Roughness Data**
  - NCAT profiling van was used to collect track profiles for right and left wheel path
  - Three data runs were used
  - IRI was calculated for each wheel path and the values were averaged (Mean Roughness Index)

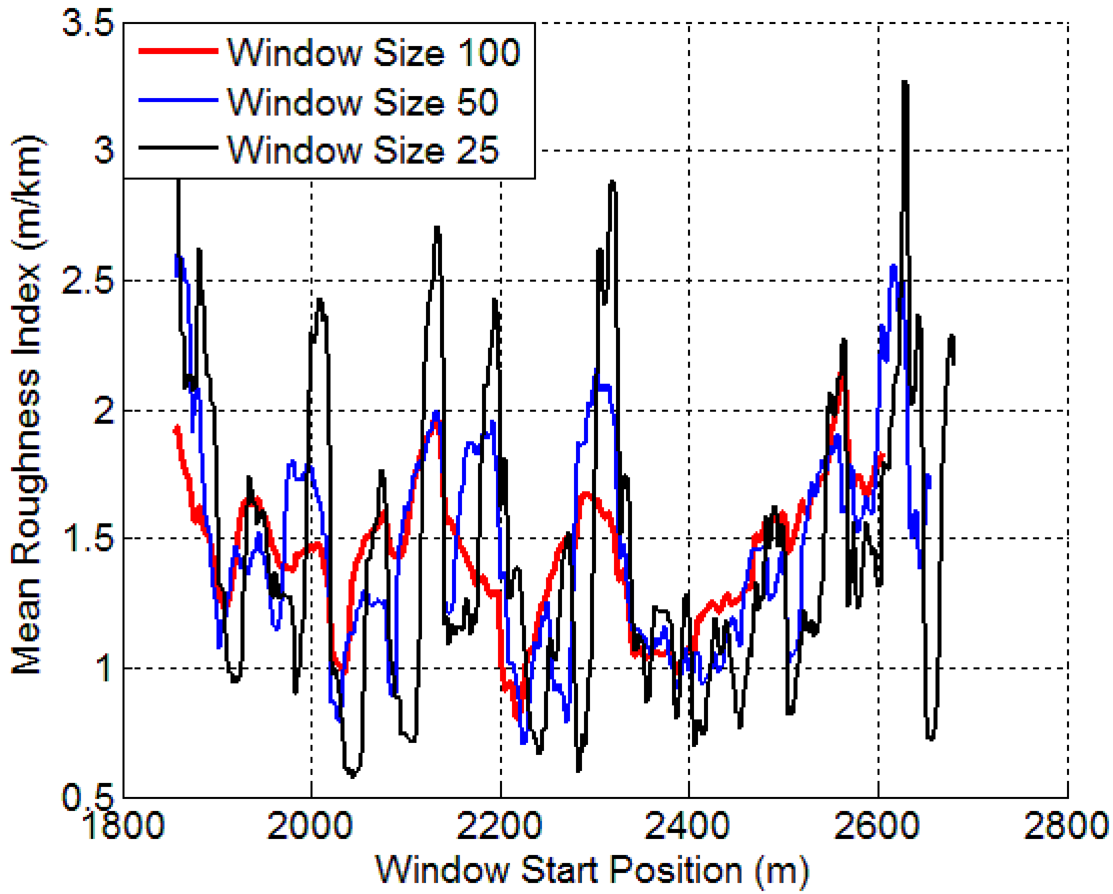




Data Collection

- Vehicle Sensor Data
  - G35 driven around track at varying speeds 40-60MPH
  - Collect GPS, IMU, and Suspension Deflections
  - Straight sections of track are analyzed
    - Road bank and sharp turns not representative of actual roads
- Sliding window was used to analyze data

Effect of Window Size



IRI Estimation Methods

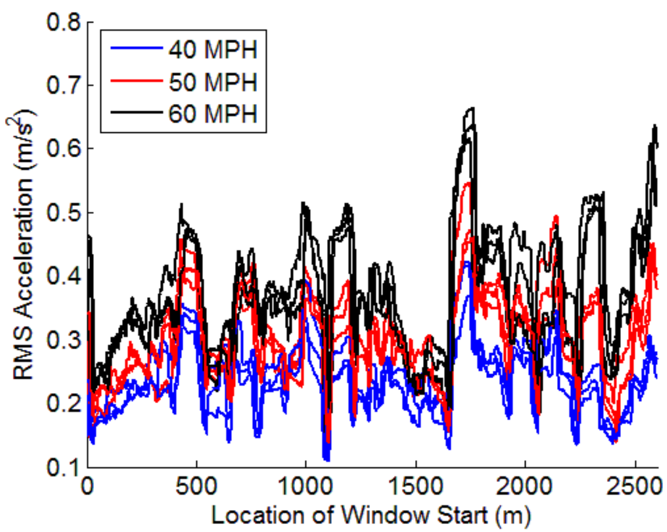
- RMS of Vibration Signal
  - Vertical Acceleration
  - Roll Rate
  - Pitch Rate
  - Suspension Deflection
- Suspension Energy
  - Potential and Kinetic Energies of unsprung mass
  - Requires differentiation of deflection
- Pseudo IRI
  - Sum deflections and divide by distance traveled

Roughness Estimation

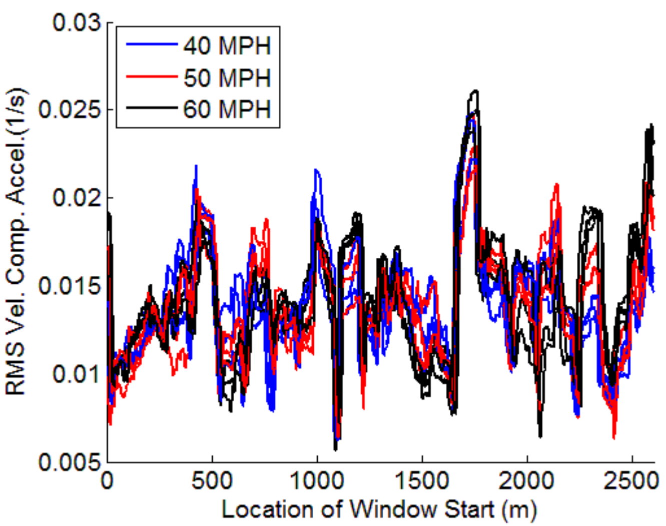
Root Mean Squared Vertical Acceleration

$$a_{z,rms} = \sqrt{\frac{1}{n}\sum_{i=0}^{n} {a_{z,i}}^2} \qquad a_{z,comp} = \sqrt{\frac{1}{n}\sum_{i=0}^{n}\left(\frac{a_{z,i}}{v_{x,i}}\right)^2}$$

Vehicle speed must be accounted for and RMS accel must be compensated



RMS Acceleration



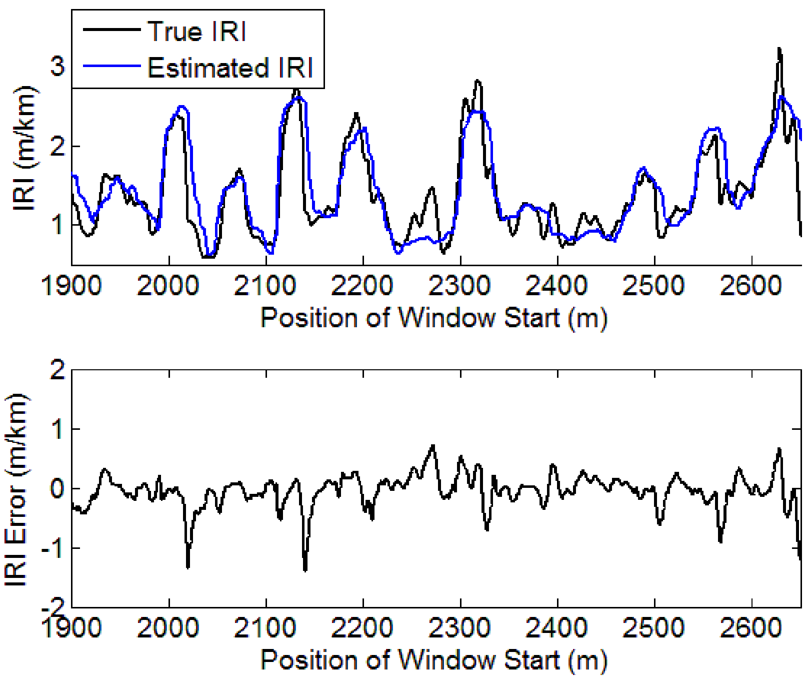
Normalized RMS Acceleration

Vehicle Calibration

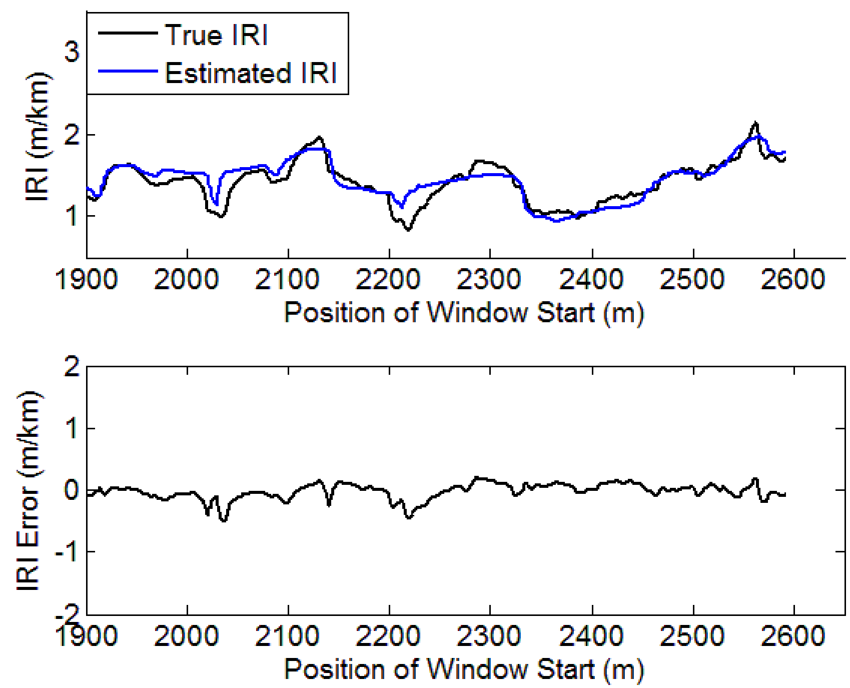
- The trend of the RMS will generally match trend of IRI
- To estimate IRI numerically it must be scaled
  - Compare to actual IRI to determine scaling
- Potential Calibration Methods
  - Driving a surveyed road
  - Similar vehicle calibration
  - Model based calibration
    - Requires vehicle parameters

Vertical Acceleration Estimated IRI

Compensated Scaled RMS Vertical Acceleration Compared to IRI



25 meter window

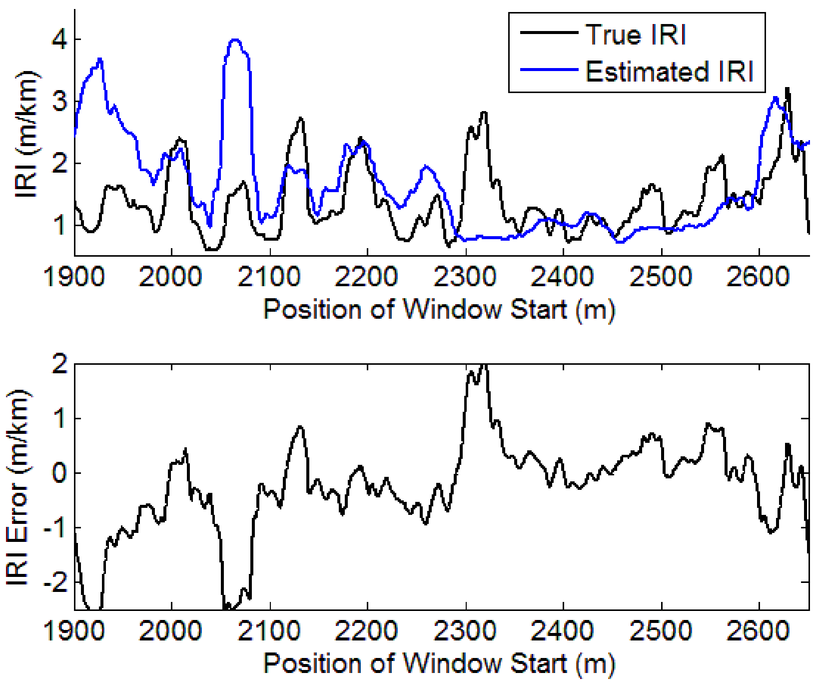


100 meter window

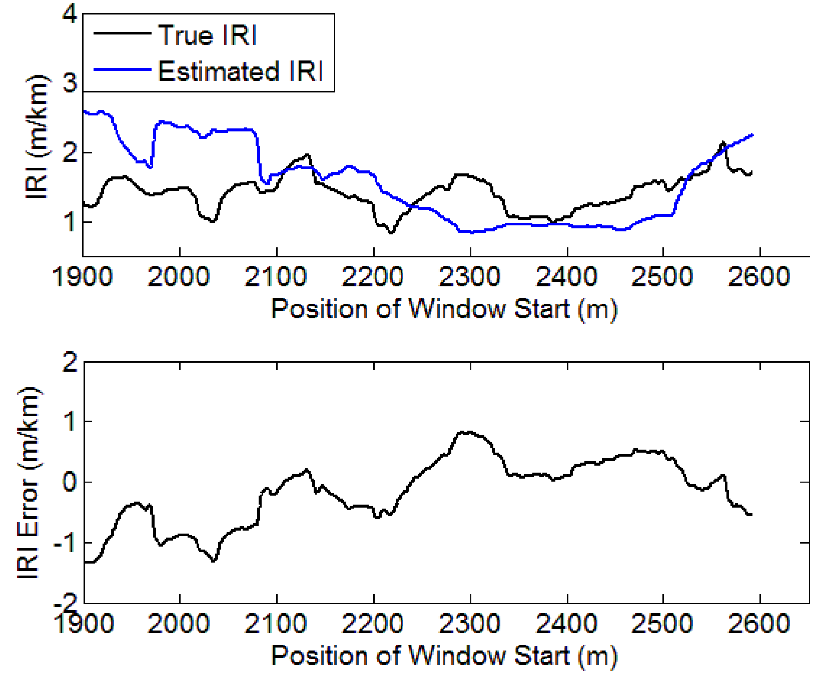
- Strong correlation between RMS vert. accel and IRI

Roll Rate Estimated IRI

Compensated Scaled RMS Roll Rate Compared to IRI



25 meter window

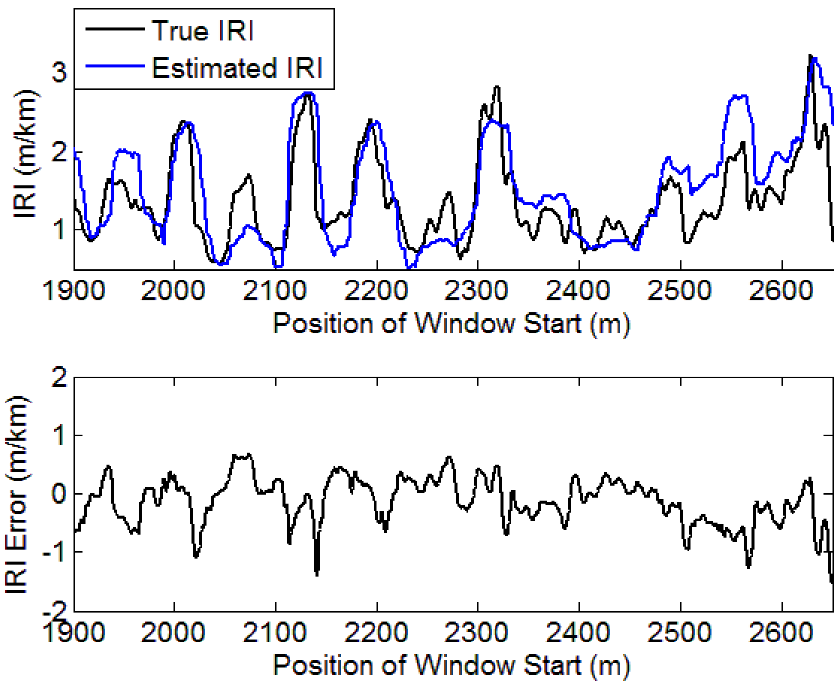


100 meter window

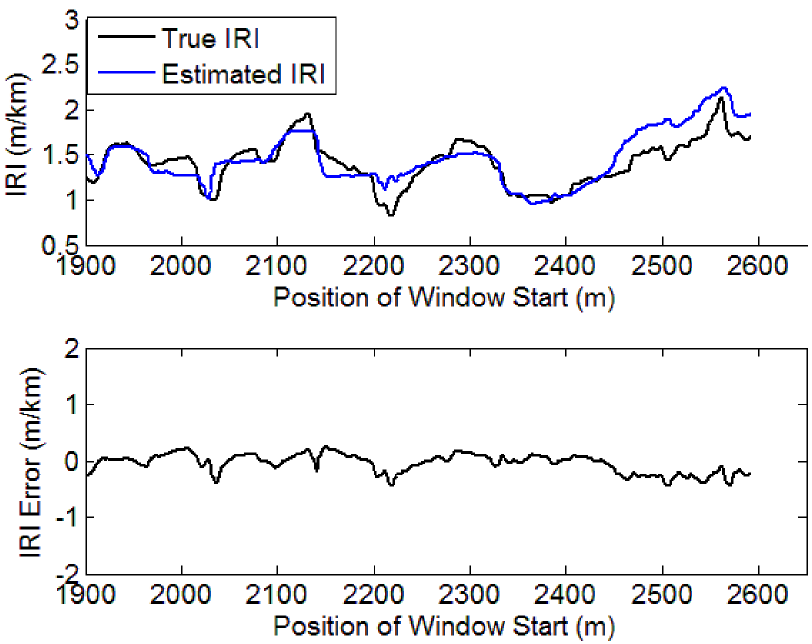
- Weak correlation between scaled RMS roll rate and IRI
- Might Stand as its own metric

Pitch Rate Estimated IRI

Compensated Scaled RMS Pitch Rate Compared to IRI



25 meter window

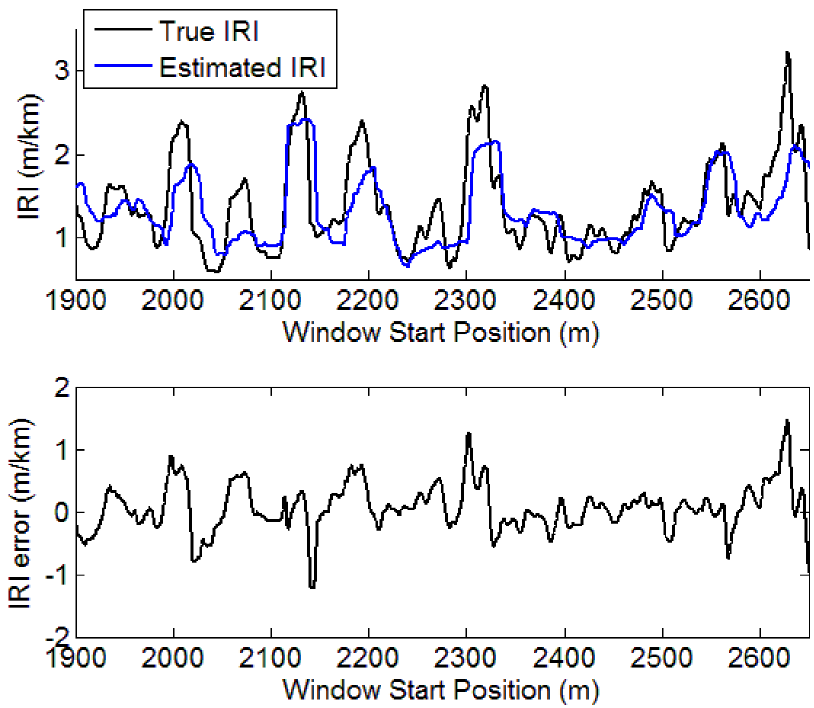


100 meter window

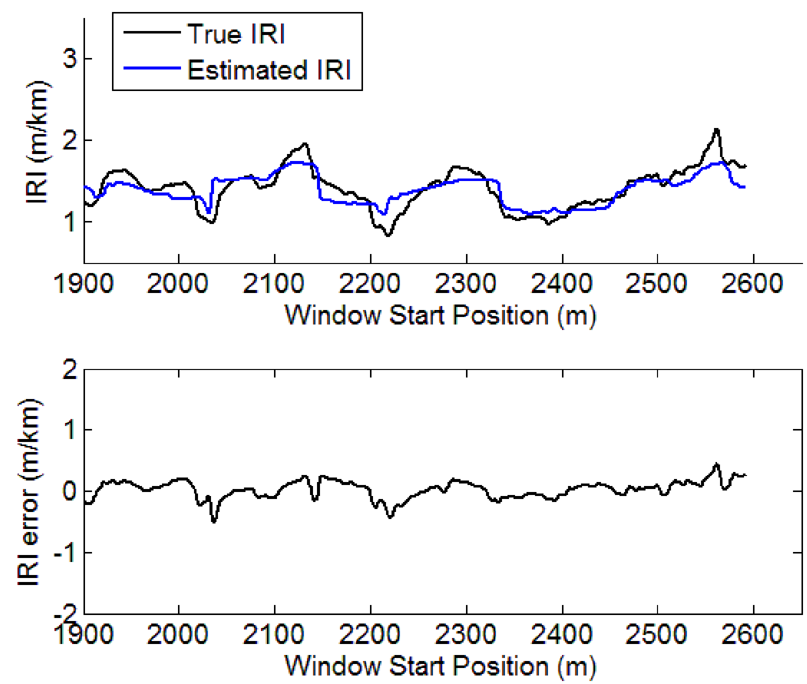
- Reasonable Correlation to IRI
- Unlikely to find pitch rate sensor on production vehicle

Suspension Deflection Estimated IRI

Compensated Scaled RMS Suspension Deflection Compared to IRI



25 meter window

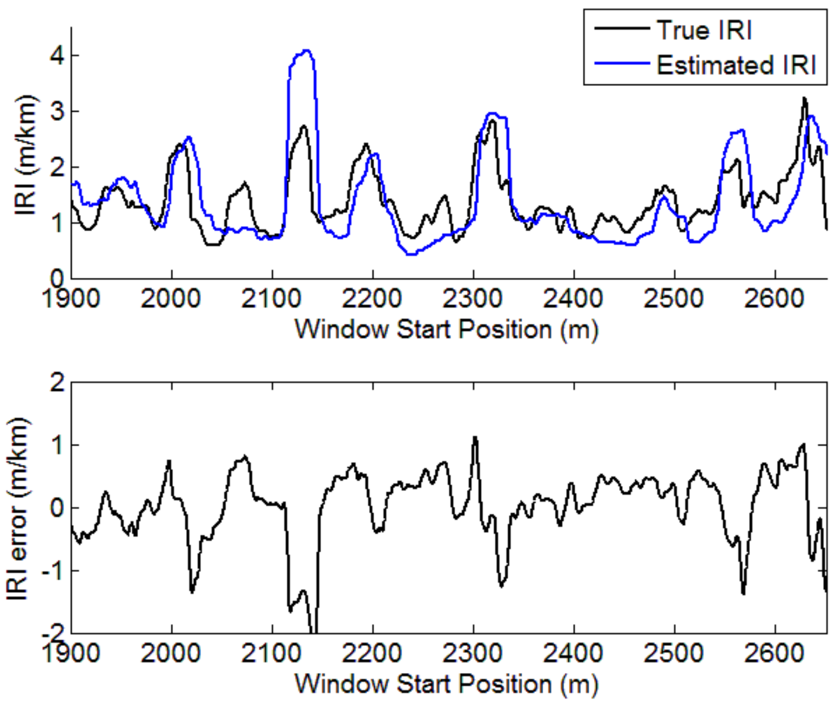


100 meter window

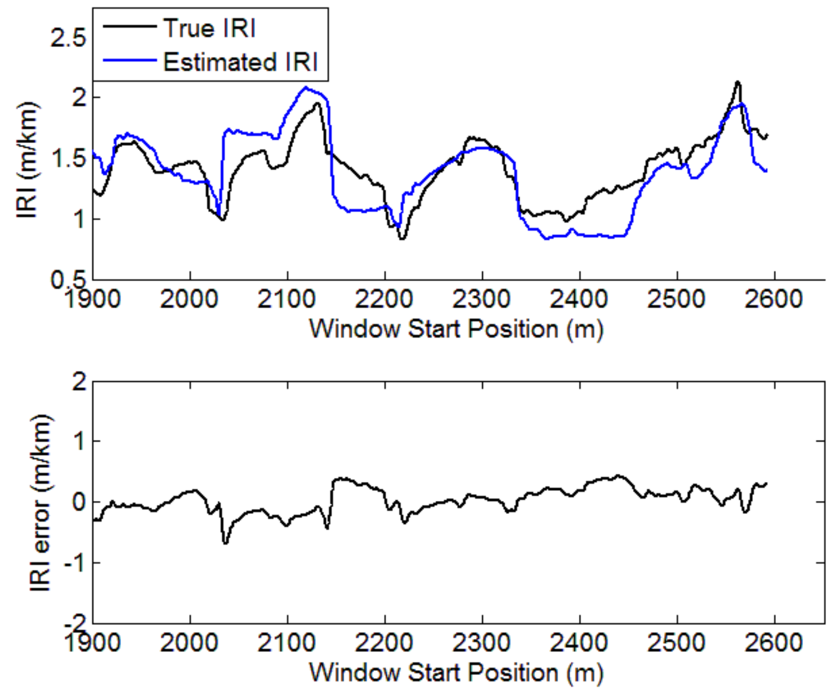
- Strong Correlation to IRI

Suspension Deflection Estimated IRI

Scaled Suspension Energy Compared to IRI



25 meter window

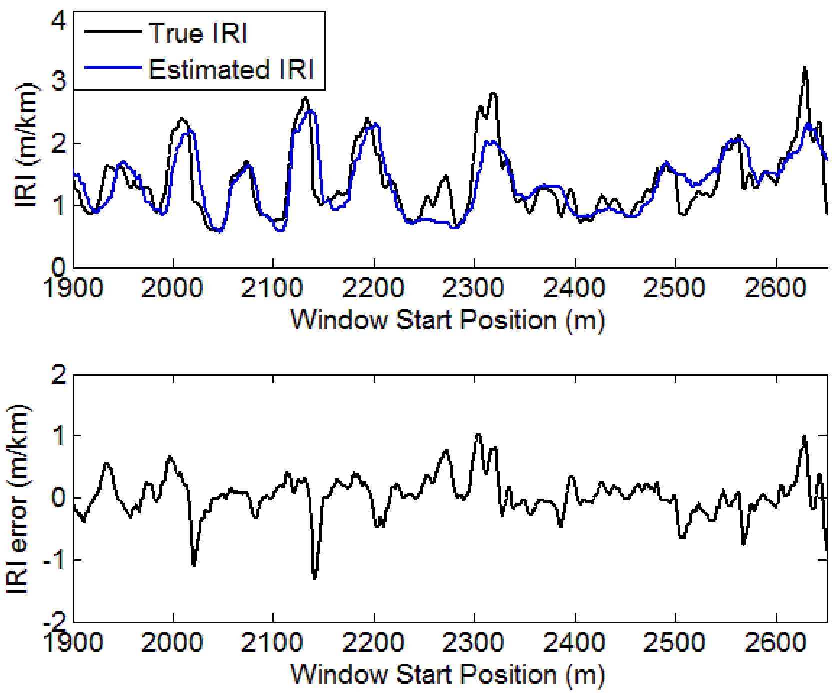


100 meter window

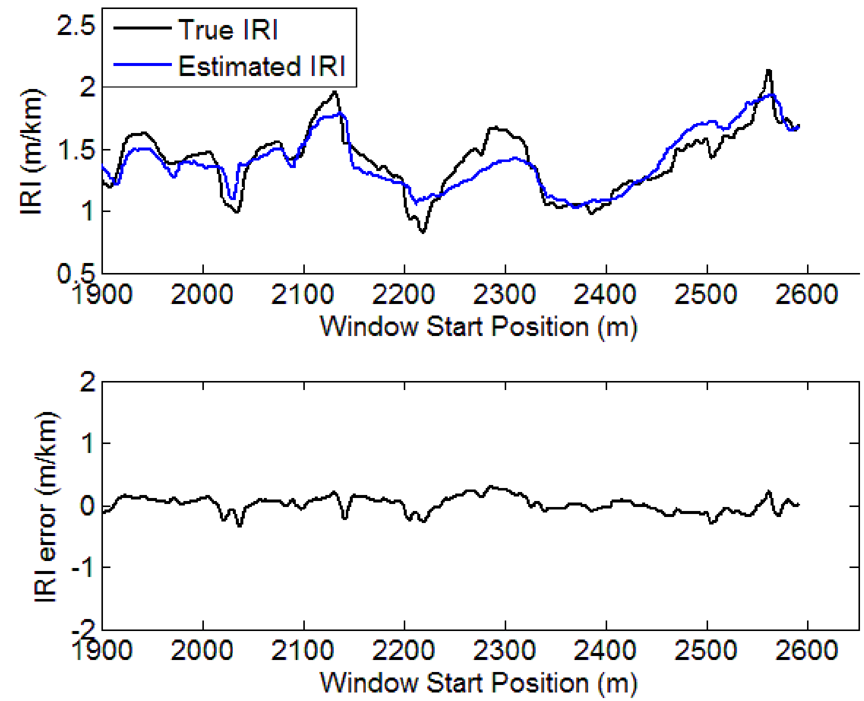
- Captures trend
- Might Stand as its own metric

Suspension Deflection Estimated IRI

Pseudo IRI Compared to True IRI



25 meter window



100 meter window

- Strong correlation with IRI

Summary of IRI Estimation Results

Table Summarizing RMS Errors for each of the IRI estimation methods

	IRI Estimation Method					
Window Size	RMS Vert. Accel	RMS Pitch Rate	RMS Roll Rate	RMS Susp. Def	Susp. Energy	Pseudo IRI
25 m	0.309	0.449	0.957	0.427	0.592	0.352
50 m	0.217	0.292	0.884	0.262	0.353	0.221
100 m	0.126	0.177	0.676	0.143	0.215	0.121

- Larger window sizes result in lower errors
- RMS Vert Accel and Pseudo IRI are most effective methods
  - IRI was developed to capture vert. accel.
  - IRI used suspension deflection of quarter car model
- Based on standard deviation of errors can estimate within +/- 0.25 m/km

Pothole Detection

Sigma Threshold Algorithm

$$find\ i : \{abs(a_{z,i}) > K * \sigma_a\}$$

- Calculate standard deviation of acceleration profile
- Identify points above a certain scaling of the standard deviation
- Finds bumps relative to the entire signal
- Computationally Inexpensive

Wavelet Transform Algorithm

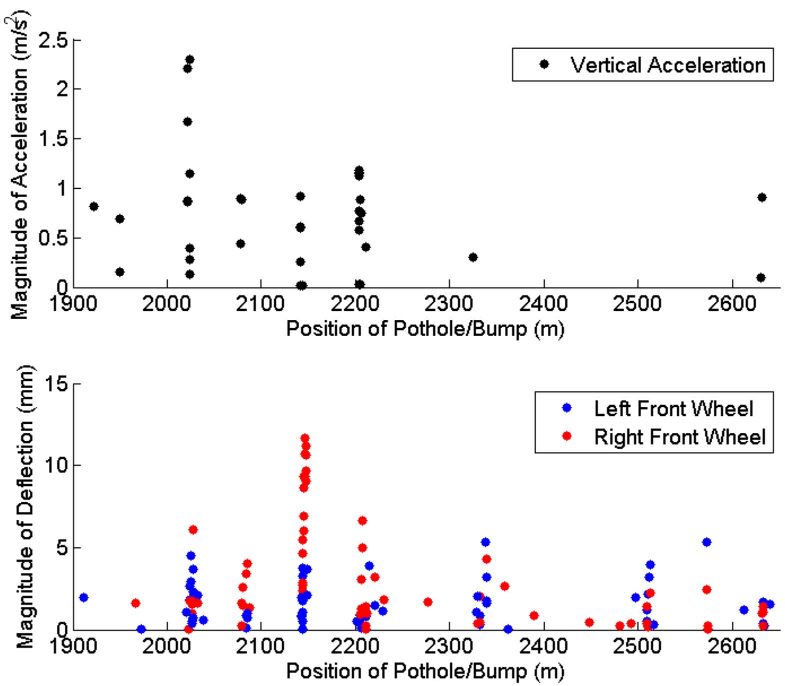
$$\psi_w(b,a) = \frac{1}{\sqrt{a}}\psi\left(\frac{x-b}{a}\right)$$

$$C_{b,a}(x) = \int_{-\infty}^{\infty} f(x)\psi_w(b,a)dx$$

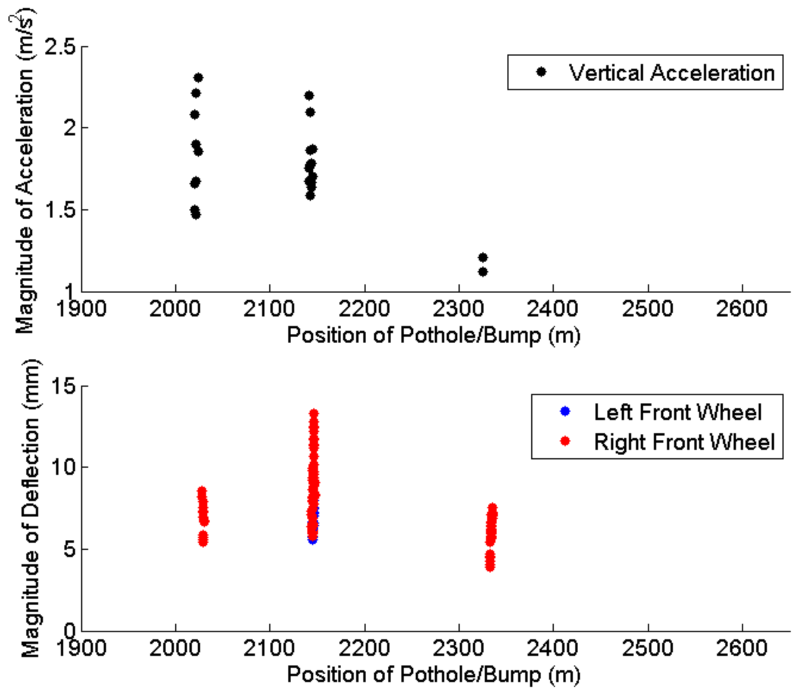
- Take wavelet transform of profile
- Perform threshold method with wavelet coefficients
- Finds bumps relative to neighboring points
- More computationally expensive

Pothole Detection

Bumps along track at 6σ threshold



Wavelet Transform Method

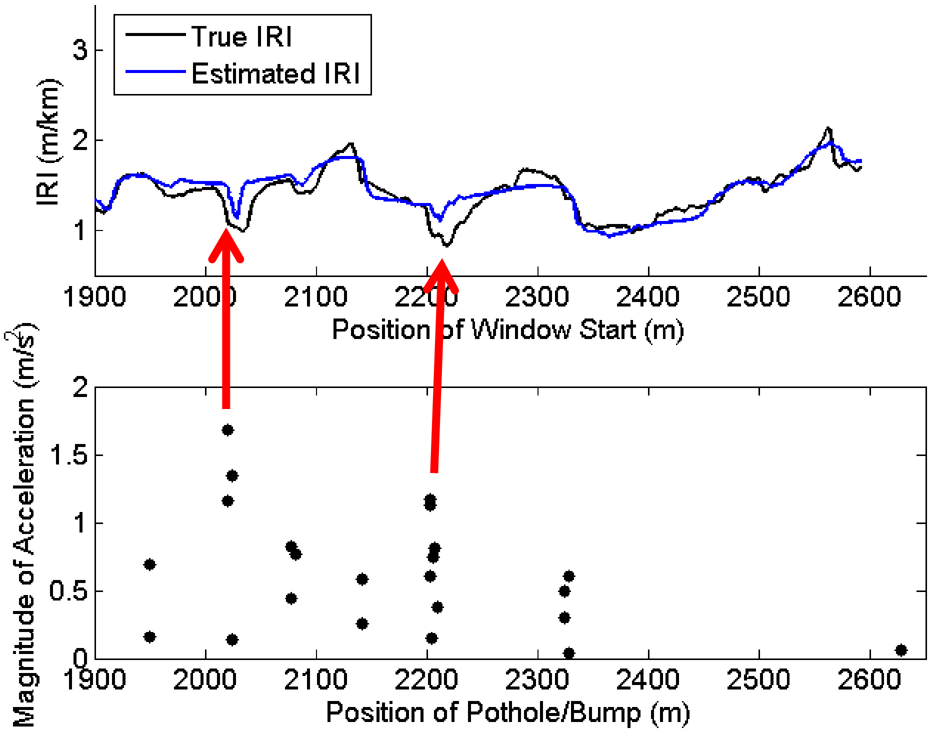


Sigma Threshold Method

Effect of Bumps on IRI Estimation

- Bumps in acceleration profile can cause error in IRI estimation

RMS Vertical Accel. Estimated IRI



DSRC Capability Testing

- DSRC Range test (Kapsch MCNU)
  - Streaming data was sent between vehicle and base station
  - Vehicle was driven away slowly until packets of data were dropped
  - Effective range was around 700m
- Bandwidth test
  - Sent data file of one lap of IMU data
  - Transmission took over 20 seconds
- DSRC not intended for sending large streams of data
  - Best to run algorithms on the vehicle and send results using DSRC

Conclusions/Recommendations

- Focused on easy to implement algorithms for near term deployment
- RMS Vertical Acceleration or Pseudo IRI can be used with good results (within 0.25 m/km)
- Sigma Threshold algorithm is recommended for pothole detection
- Calibration is important for quantitative accuracy
  - trends can be captured without calibration

Deployment Analysis

Current State of the Art: Connected Vehicles

- Sensor set on today's automobiles relevant to pavement assessment
  - Rollover Stability Control / electronic stability control: vertical accelerometers and gyroscopes now on millions of today's cars
  - suspension deflection sensors in vehicles equipped with active or semi active suspensions
    - Examples:
      - Volvo S60R, V70R, S60, V70 and S80
      - Ford S-Max and Galaxy
      - Audi A6 and A6 Avant
- Modes of motion which correspond most closely with the IRI are:
  - vertical acceleration, pitch rate, suspension deflections
- These sensors used in estimating IRI in this project.

Current State of the Art: Connected Vehicles

- Pavement-relevant sensor data available on the vehicle Controller Area Network (CAN) databus
- OnStar example
- Unlikely this data can be tapped by aftermarket systems

Current State of the Art: Probe Messaging

- Data Reporting
  - Commercial wireless
  - DSRC (low latency feature not required)
- Probe Data Deployments
  - 1st Gen: DDG Germany (2005)
    - 70,000 vehicles
    - 30M records daily
    - High communications costs
  - 2nd Gen: BMW Extended Floating Car Data
    - Data management
    - exception-based reporting
    - Greatly reduced communications costs
  - Similar probe data systems expected to enter US market in 2011-2012 timeframe

Current State of the Art: Probe Messaging

- Penetration Rate of Equipped Vehicles
  - Traffic jam detection:
    - under 10% penetration (BMW)
  - Pavement quality detection:
    - Slowly changing
    - Penetration assumed as 1% for purposes of this study

Current State of the Art: Probe Messaging

- Standards for probe data messaging
  - ISO 22837 (Vehicle Probe Data for Wide Area Communications)
  - SAE J2735 (Dedicated Short Range Communications Message Set Dictionary)
- SAE J2735 defines:
  - probe data message frame
  - a wide array of probe vehicle data
- Key Data Elements
  - DE_VerticalAcceleration
    - signed vertical acceleration in units of 0.02G over a range of +1.5 to -3.4G
  - DE_VerticalAccelerationThreshold
    - preset threshold for vertical acceleration fpr each wheel

Deployment Support and Analysis

- Preliminary Concept of Operations
  - Purpose of System
  - Vision of PDPM
  - Assumptions and Constraints
  - User-Oriented Operational Description
  - Relationship to National ITS System Engineering Architecture Update
- System Requirements
  - Vehicle
  - Data Provider
  - State/Local DOT
  - Operational Needs

Deployment Risks / Constraints / Opportunities

- Wireless Media
  - commercial wireless services:
    - vehicle transmits data via cellular communications network to the data provider
  - DSRC:
    - vehicle stores data in on-board buffer
    - transmits entire dataset to an RSE when encountered
    - Information routed through backhaul network to processing entity
  - Which is the best way?

Deployment: Wireless Media

- Commercial wireless services
  - available now
  - provide sufficient bandwidth and communications latency for probe data
  - bandwidth must be paid for
- DSRC
  - "free" to use once they exist (but RSEs have to be installed and maintained by DOTs)
  - if RSE's are installed for other purposes (i.e. SPAT) then the DSRC link could provide a channel for probe data
  - OT could assimilate the data for their pavement management program, or forward the data to a data provider for processing
  - Since data collected by the vehicle is held until the vehicle encounters an RSE, cellular transmission of data is the only viable option in rural areas where RSEs are not deployed
- Conclusion
  - First generation probe data systems are expected to be operating within the U.S. in the next few years
    - before DSRC roadside units are available in significant numbers
  - first probe data systems will build on the European approach of commercial wireless services
  - first generation probe systems should be viewed as using commercial wireless services

Deployment Risks / Constraints / Opportunities

- Probe Data Management
  - implements "back channel" to vehicles via broadcast
  - instructs vehicles within a certain region to:
    - increase/decrease reporting frequency
    - increase/decrease reporting accuracy
    - report data only when the vehicle is within a specific geographic area
  - When DOT wants detailed pavement data in a specific area, use probe data management to focus reporting on a particular road section.
  - And if quality of a particular roadway is well known, instruct vehicles not to report pavement-relevant probe data
    - conserving communications bandwidth

Deployment: Event Based Reporting

- If nothing of note is happening on the roadways, why use communications resources to report it?
- Event-based probe reporting
  - Rather than collecting and reporting raw probe data continuously, the vehicle pre-processes the data to flag pre-defined "events."
  - Typical events include traffic jam, slippery road, potholes, and weather events.
  - Probe Data Management can be used to set thresholds of reporting, such as a specific vertical acceleration value to detect certain types of potholes
  - Initially PDPM will gather data for all roads to create an IRI map
    - continuous data reporting is needed
  - Once a baseline is created, event-based probe reporting can be useful to detect changes in pavement quality

Deployment Risks / Constraints / Opportunities

- Business Case Considerations
  - Cars sold on a national basis
  - Car-maker requires consistency in the software for probe data reporting across their fleet nationally
  - If they are transmitting a packet of probe data for pavement quality, this will occur no matter where the car is.
  - The cost of transmitting these messages must be covered.
  - Therefore probe-based assessment of pavement quality does not lend itself to a state-by-state deployment.
  - Role for FHWA and state DOTs to develop a feasible business case, based on collective action.

Deployment Risks / Constraints / Opportunities

- Business Case Considerations – One Model
  - State DOTs contract with traffic data providers to add pavement quality information to their offerings.
  - Requirement would need to come from a sufficient number of states to make the data collection cost effective.
  - On a per-mile basis the traffic data provider would likely charge much more for pavement quality data than for traffic data, as they have fewer customers for pavement data
  - DOT customers would have to cover the full cost of collecting, transmitting, and processing this data.
  - Alternative scenario:
    - If drivers can be given advance notice of potholes, a commercial business case can be built

Deployment Risks / Constraints / Opportunities

- Deployment Risks
  - market penetration of vehicles equipped to provide probe data may not occur at a high enough rate to create sufficient data for pavement management
  - the business case may falter unless states, cities, and the federal government work together to create a stable market of sufficient size to attract investment by data providers and car manufacturers

Deployment Risks / Constraints / Opportunities

Deployment Constraints

- the rate at which equipped vehicles will enter the vehicle fleet will be constrained by market conditions
- the quality of pavement data will depend on the performance of the sensors chosen by the car manufacturers for their vehicles

Deployment: Timeline

- Timeline for Sufficient Equipped Vehicles
  - How long until 1% of vehicles are reporting?
    - Approxmately 2.5M vehicles
  - Assume 12M vehicles sold annual
    - Equippage rate rising from .5% to 5% over 2014 – 2021
  - By 2021 about 2.5M vehicles equipped
  - Useful data being supplied much earlier

AUBURN UNIVERSITY

Equippage Timeline

Year	% equipped	# vehicles	Cumulative sum
2014	.5	60,000	60,000
2015	1	120,000	180,000
2016	1	120,000	300,000
2017	2	240,000	540,000
2018	2	240,000	780,000
2019	4	480,000	1,260,000
2020	5	600,000	1,860,000
2021	5	600,000	2,460,000

GAVLAB

Deployment: Timeline

- What about aftermarket systems?
  - "Here I Am" devices can create a greater density of communications interaction
  - PDPM application requires reliable kinematics data from accelerometers and rate gyros.
    - must be mounted on the vehicle in such a way that the road surface components are transmitted to the sensor
    - Aftermarket/HIA devices, as defined by the USDOT program, do not lend themselves to this type of installation
    - It is doubtful HIA devices would contribute to creating PDPM data
  - However, new requirements could be defined such that HIA devices incorporate the accelerometers and rate gyros needed for PDPM.

Deployment Risks / Constraints / Opportunities

- ***Vehicle/Data Costs***
- Estimate additional air-time cost per car for sending pavement-relevant data is $5 per vehicle per year.
  - Covers only transmitting event-based data, with reporting thresholds the DOTs could adjust.
- PDPM fleet of 2.5M vehicles is estimated to be sufficient.
- Annual cost for transmission of data: $12.5M
- Estimate probe data processor would add another $5 per vehicle per year for their services.
- The total costs in this scenario:
  - $25M annually for national coverage.
- Pricing from a service provider would have to recoup initial costs from a relatively small pool of states.
- Assuming 10 states form the initial market the cost per state is $2.5M.

Deployment Risks / Constraints / Opportunities

Current Pavement Assessment Costs

- Cost of in-house delivery of network level IRI data:
  - between $10 and $20 per lane mile, averaging approximately $15 per lane mile
- Cost of network level IRI data collected by out-source contractors:
  - between $20 and $30 per lane mile, averaging $25 per lane mile

Deployment Risks / Constraints / Opportunities

Estimated Costs for IRI Data Collection in Selected States

Location	Lane Miles	Cost at In-House Rate ($15/mile)	Cost at Contracted Rate ($25/mile)
Alabama	200,000	$3.00M	$ 5.00M
California	390,000	$5.85M	$ 9.75M
Michigan	250,000	$3.75M	$ 6.25M
Texas	650,000	$9.75M	$16.25M
Virginia	160,000	$2.40M	$ 4.00M
USA	8,500,000	$127.5M	$212.5M

Deployment Risks / Constraints / Opportunities

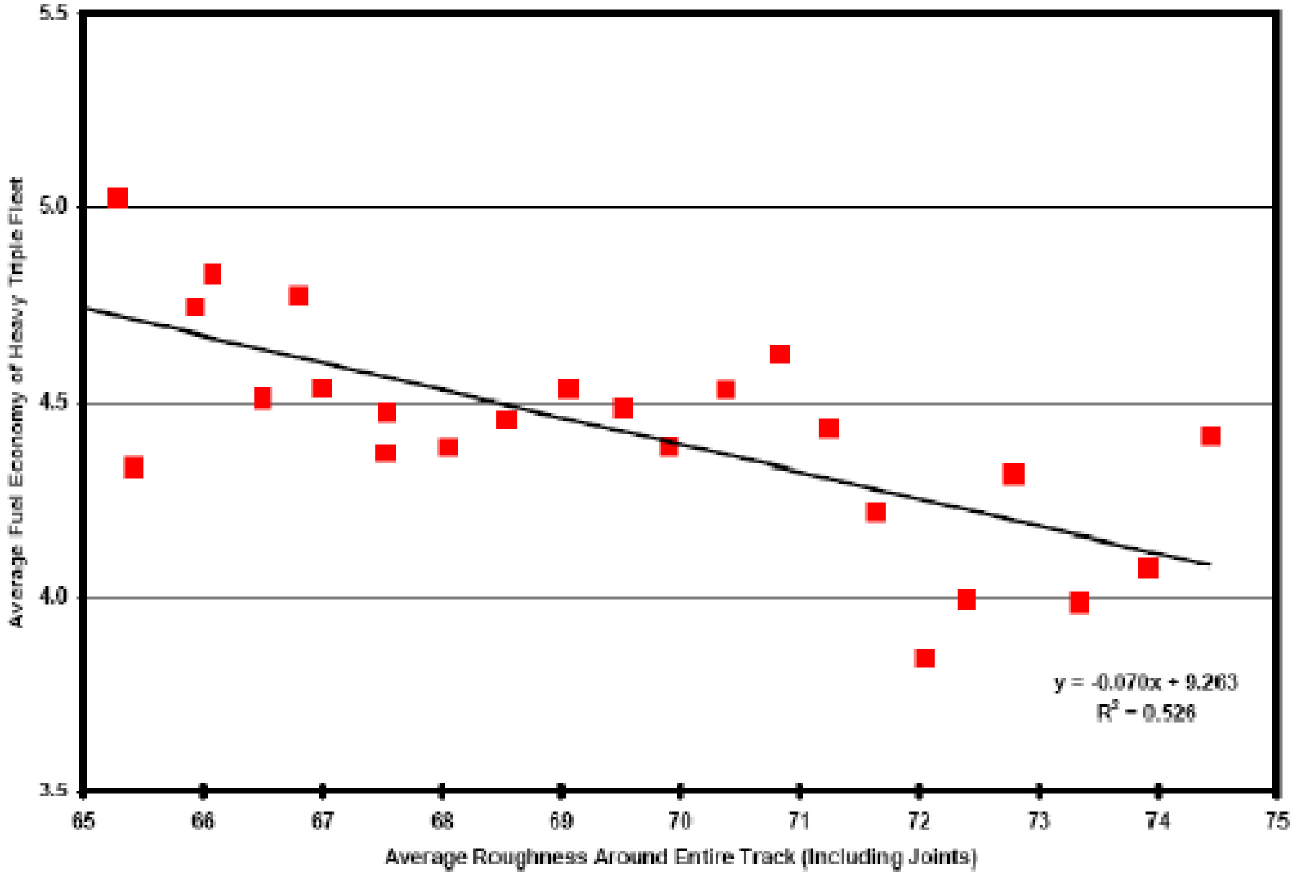
- Cost Comparison
- $25M cost for national PDPM is between 12-20% of the national cost using current methods
  - depending on the approach used (in-house versus contracted)
- Early deployment scenario
  - ten states bearing the $25M cost burden
  - cost advantage for PDPM depends on the lane mileage within the state
- PDPM costs of $2.5M per state would be lower for all the states shown except for Virginia, compared to current methods.

Deployment Risks / Constraints / Opportunities

- The current collection method of acquiring network level IRI data conducted by the states is a reliable process.
  - Data delivered for the roads and lane-miles targeted by the state with their own resources.
- PDPM, relying on independent actors, is a different animal.
  - provides extensive coverage on a daily basis
  - Yet specific roads and the amount of data collected is uncertain.
- IRI data collected by states could be phased out in the far future when PDPM-reporting vehicles are ubiquitous…
- … but there will inevitably be a transition period as the market matures and increasing numbers of vehicles are equipped.

Fuel Economy and Pavement Quality

And when "green" matters in budget justifications….



Conclusions / Recommendations

- PDPM offers the potential for cost-effective pavement assessment using sensors already on today's automobiles.
  - Roll-out of probe data services in the U.S. is expected to begin near-term
  - However, PDPM does not offer the type of business case to car-makers that traffic and weather information do.
  - Infrastructure community needs to stimulate a PDPM pavement data market at the national level, to motivate data providers to seek this information, which will motivate car companies to provide it.
- Note: implementation of PDPM requires a shift in philosophy regarding allocation of resources traditionally used for IRI measurements.
  - shift is in defining "how much is good enough" when using non-deterministic data sources which may be lower cost

Conclusions / Recommendations

- Recommendation:
  - Initiate a pilot program with one or more states plus a car company who is a leader in probe data
  - Objective: take study results to a real-world setting
    - gain experience with both the quality of the data as well as reporting management techniques.
  - pilot could also engage data service providers to begin to conceptualize a delivery mechanism to state DOTs.