Calibration of a mobile application for estimating the IRI in urban areas in Peru

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Motivation

Figure: Piura, Peru (source: https://commons.wikimedia.org/w/index.php?curid=9395222)

Motivation

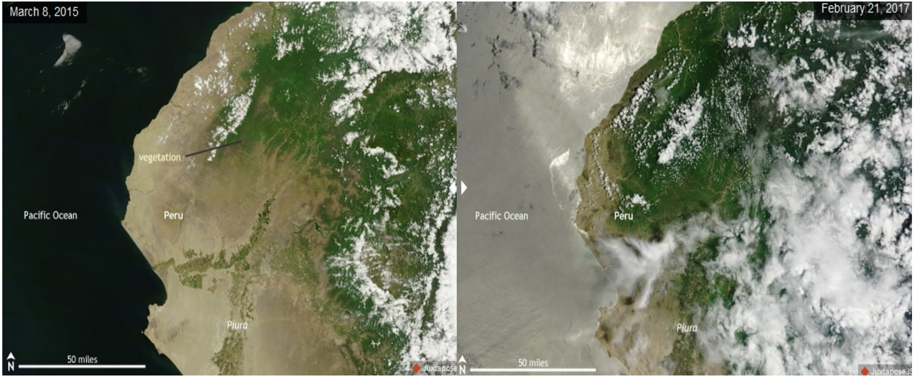


Figure: source: NASA MODIS satellite images from Worldview, NOAA Climate.gov

Piura experienced up to 10 times more rain than normal, leading to flooding and landslides in the usually semi-arid coastal landscape.

Motivation

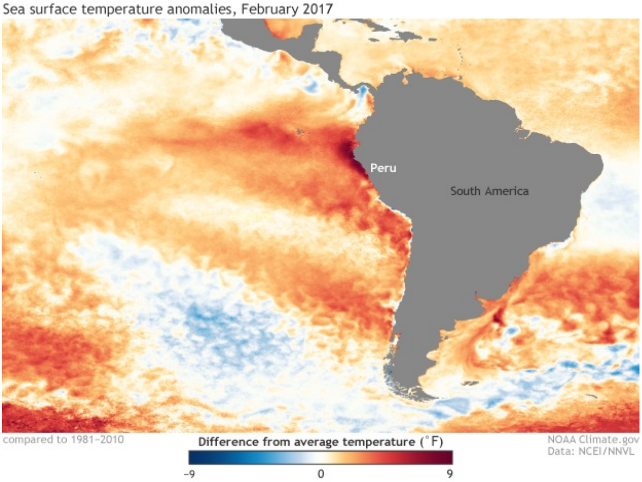


Figure: Sea surface temperature difference from average, Feb. 2017. Source: NOAA Climate.gov

Motivation

Figure: The 2017 *El Nino Costero* flooding in Peru

The 2017 *El Nino Costero* flooding in Peru was highly destructive. It lasted three months, affected over 1.5 million people, caused 162 deaths, and damaged thousands of homes (Venkateswaran et al., 2017).

Motivation

- How to measure the the road surface roughness condition objectively?

- How to monitor the road surface condition on time?

Motivation

The International Roughness Index (IRI) is a standard worldwide indicator for measuring the road roughness condition which is the support for the evaluation and management of the road performance.

High precision instruments are expensive and have less availability.

Smartphones are potentially useful to be adopted as a cost-effective and easy to implement tool.

The mobile apps estimate the IRI through regression equations.

Project goal

Determine the road roughness condition objectively using mobile applications that estimate the IRI taking into consideration Peruvian reality through a regression model that will allow us to calibrate the observed measurements to the standard ones.

Overview

Basics

What is IRI?

Road roughness is understood as the variation in surface elevation along a road that causes vibrations in traversing vehicles.

The standard summary statistic that quantifies this variation is the International Roughness Index (IRI).

It was proposed in 1982 by a group of experts (from Brazil, England, France, USA y Belgium) from the World Bank. They define the IRI as, (Sayers et al., 1986)

> *"a ratio of the accumulated suspension motion of a vehicle (in, mm, etc.), divided by the distance traveled by the vehicle during the test (mi, km, etc.)."*

IRI scale

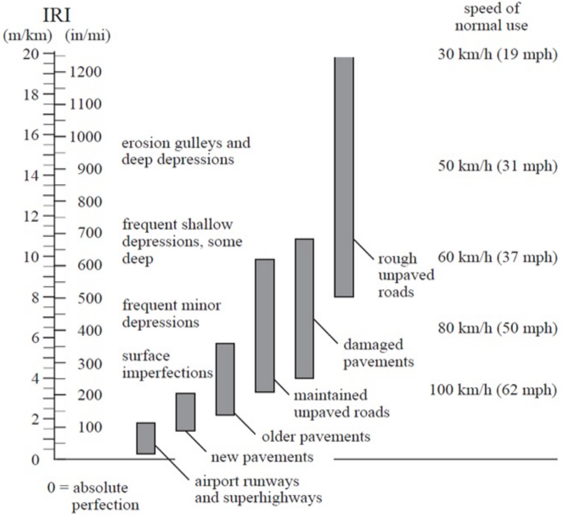


Figure: IRI scale (Sayers and Karamihas, 1998)

Instruments

Class 1: high precision.

Figure: Mounted profiler

Figure: Walking profiler

Instruments

Class 2.

Figure: Profilograph

Figure: Rod and Level

These can become class 1 instruments if the measurements are taken every 250 mm (9.84 in).

Instruments

Class 3.

Figure: “Merlin“

Figure: Accelerometers

Summary of measurement instruments

Table: Roughness data collection equipment

	Device	Initial cost	Data collection cost	Availability
Class 1	Profilers	High	Low	Medium
	Rod and level	Low	Impractical	Easy
Class 2	Profilographs	Low	Impractical	Medium
Class 3	Merlin	Low	Impractical	Easy
	Accelerometers	Low	Low	Easy

Background

Background

Road roughness condition is a linear function of magnitude of acceleration and average speed, and a linear function of the accelerometer, gyroscope and the average speed (Douangphachanh and Oneyama, 2014a), (Douangphachanh and Oneyama, 2014b).

Islam et al. (2014) find that the IRI measurements from the mobile applications are sensible to data collection rates, vehicle speed, and type of vehicle produced.

Changes in device type, vehicle type, and mounting arrangement significantly impacted IRI variance, while vehicle speed (50 km/h and 80 km/h) did not (Hanson et al., 2014).

Higher IRI accuracies can be achieved in low traffic conditions, where constant speeds can be maintained (Cruz and Castro, 2015).

Opportunity for improvement

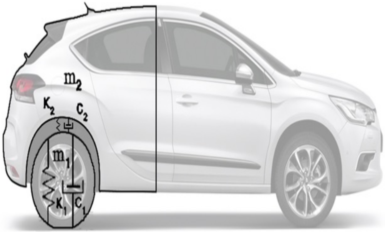
None of these studies has performed a formal DOE.

Randomization is not mentioned.

At most, they have conducted a one factor at a time experiment.

Methodology

IRI calculation by its definition



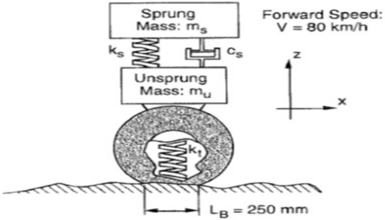


FIGURE 2 **Quarter-car model.**

Figure: Cuarter car model

Cuarter car model

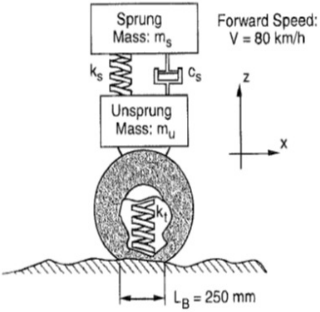


FIGURE 2 Quarter-car model.

The equations of motion for the quarter-car model are derived from Newton's second law, force = mass x acceleration (Sayers, 1989).

$$m_s\ddot{z}_s + c_s(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) = 0$$

$$m_u\ddot{z}_u + c_s(\dot{z}_u - \dot{z}_s) + k_s(z_u - z_s) = k_t(z_p - z_u)$$

Cuarter car model

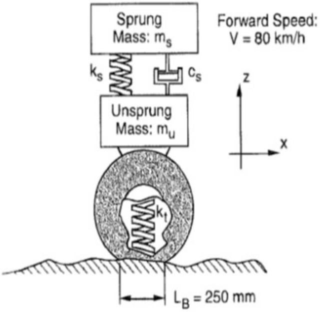


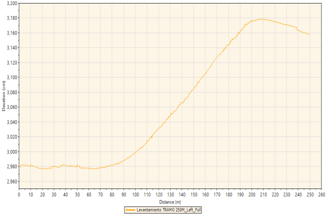
FIGURE 2 Quarter-car model.

The actual IRI is an accumulation of the simulated motion between the sprung and unsprung masses in the quarter-car model, normalized by the length L, of the profile (Sayers, 1995):

$$IRI = \frac{1}{L}\int_0^T |\dot{z}_u - \dot{z}_s| dt$$

Cuarter car model

We can solve the quarter-car model differential equations using different approaches. We could use numerical approximation (through Taylor expansion), or by simulations.



The input to the IRI calculation is the longitudinal profile of the road.

Longitudinal profile

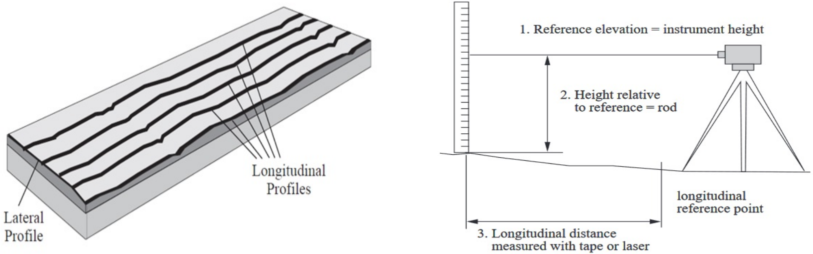


Figure: Longitudinal profiles (Sayers and Karamihas, 1998)

Profile measurement

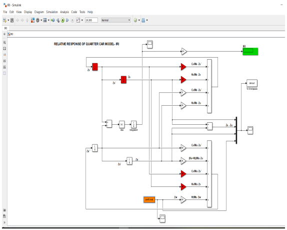
The IRI definition describes a method for computing a roughness index for a single longitudinal profile of arbitrary length (Sayers, 1995).

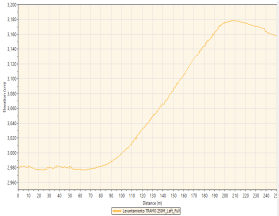
The quality of the profile measurement depends on

- The quality of the equipment, and
- The methodology used to make the measurement.

Some of the roads selected in pilot

Calculating the IRI






```r
########### IRI calculation ############################
######################################################
IRIcalc <- function(x,y,DX){
  y1 <- c(); L <- length(x)
  Z <- matrix(,4,L)
  #filter
  Lb=0.250
  K=max(1,round(Lb/DX))
  if (K==1){hps <- y}else{
    for (i in k:L){
      hps[i] <- mean(y[i:(i+K-1)])
    }
  }
  hps1 <- rep(NA,L)
  hps1[(K+1):L] <- hps[1:(L-K)]
  yp <- (hps - hps1)/(K*DX)
  #initialize
  id <- 11/DX
  Z[1,1]<- (y[id+1]-y[1])/11; Z[2,1]<- 0
  Z[3,1]<- Z[1,1]; Z[4,1]<- 0
  for (k in (K+1):L){
    for (i in 1:4){
      Z[i,k] <- PR[i]*yp[k]
      for (j in 1:4){
        Z[i,k] <- Z[i,k] + ST[i,j]*Z[j,k-1]
      }
```

Table: IRI for each sample

Sample	IRI
Section 1	4.243
Section 2	4.447
Section 3	
Section 4	6.173

Forward regression - inverse regression

We assume a linear regression as appropiate for the forward regression where the IRI measurements from the Rod and Level as the regressor, and those from the App as the response:

$$y_i = \beta_0 + \beta_1 x_i + \epsilon_i$$

where ϵ_i's are iid as $N(0, \sigma^2)$.
Note that an important assumption is that the x_i's are measured with negligible error.

The problem is to make inferences about x based on y.

The linear calibration problem

Let y_{new} be the future IRI measurement from the App, then the estimated x_{pred} is:

$$\hat{x}_{pred} = \frac{y_{new} - \hat{\beta}_0}{\hat{\beta}_1}$$

To find a prediction interval for x_{pred}, note that this involves the ratio of two dependent normal random variables. Parker et al. (2010) use Delta Method to obtain and asymptotic approximation for the variance.

Forward regression - inverse regression

A $(1-\alpha)100\%$ prediction interval for x_{pred}, (Parker et al., 2010),

$$\hat{x}_{pred} \pm t_{1-\frac{\alpha}{2},n-2} \frac{\hat{\sigma}}{\hat{\beta}_1} \sqrt{1 + \frac{1}{n} + \frac{(\hat{x}_{pred} - \bar{x})^2}{S_{xx}}}$$

Comparison with reverse regression

$$x_i = \delta_0 + \delta_1 y_i + \epsilon_i^*$$

Note that this violates the assumption that the regressor is measured with negligible error.

Parker et al. (2010) show that both (inverse and reverse approaches) give biased predictions, and that both increases as σ increases. The inverse approach has less bias as x is predicted away from 0 (assuming centering and scaling). The bias in the inverse regression decreases as n increases.

IRI measurements

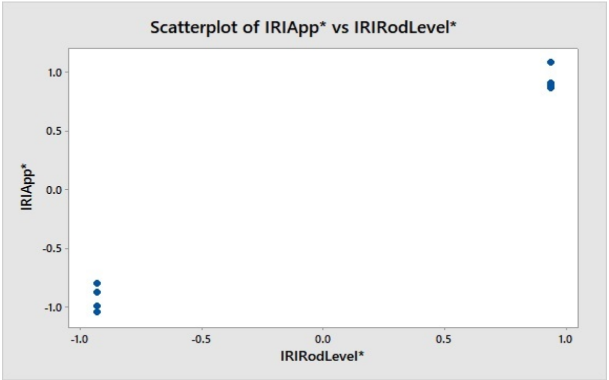


Figure: Centered and scaled IRI measurements from App vs. Rod and Level when using small vehicle at 45 km/h (28 mph)

Experiment

Two-level factors: Characteristics of the sections (HTC), Type of vehicle (HTC), wheel pressure (HTC), number of people in the vehicle, speed of the vehicle, position of the cellphone, direction if the road has slope.

Since sections are hard-to-change (HTC), and for each section we also have other 2 HTC factors, we use a Split-split-plot design.

Split-split-plot design

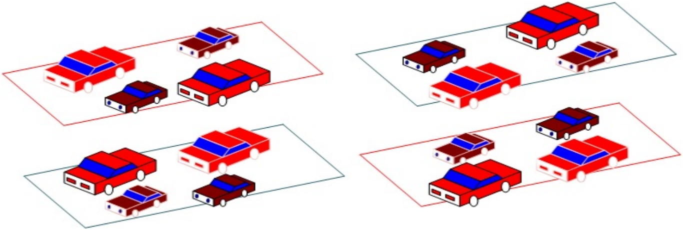


Figure: IRI estimation split-split-plot design

Section characteristics → vehicle and pressure (2^2) → speed, direction and people (2^3)

Preliminary results

First order split-plot analysis

Fitting a first-order model with interactions:

$y =$ WP factors + WP error + SP factors + WPxSP interactions + SP error

$$IRIapp = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_1 2 Z_1 Z_2 + \sigma_\gamma^2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{34} X_{34} +$$

$$\beta_{13} Z_1 X_3 + \beta_{14} Z_1 X_4 + \beta_{23} Z_2 X_3 + \beta_{24} Z_2 X_4 + \sigma_\epsilon^2$$

Whole plot analysis

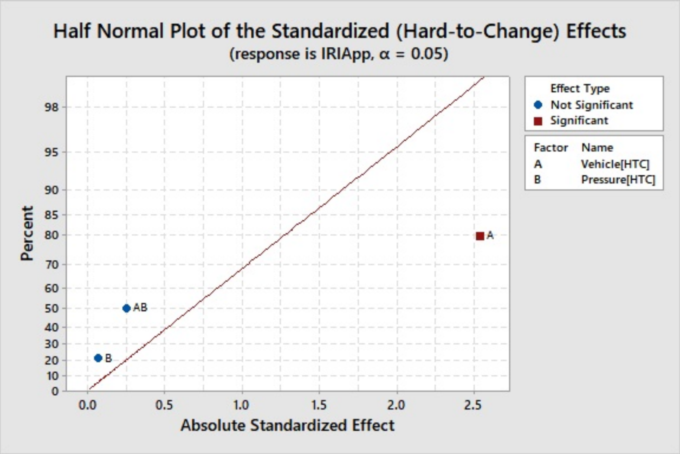


Figure: Whole plot analysis

Split plot analysis

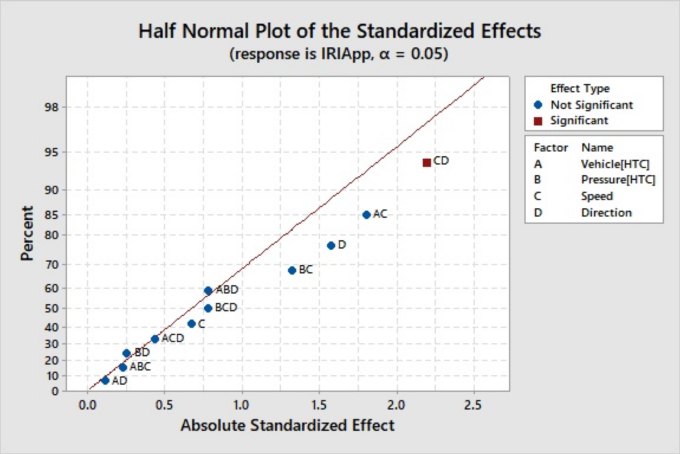


Figure: Split plot analysis for IRI measurements from App

Split plot analysis

Table: Split plot analysis for IRI measurements from App

Source	DF	SS	MS	F	P
Blocks	2	5.30992	2.65496	18.13	0.003
Vehicle[HTC]	1	0.94094	0.94094	6.42	0.044
Pressure[HTC]	1	0.00056	0.00056	0.00	0.953
Vehicle[HTC]*Pressure[HTC]	1	0.00918	0.00918	0.06	0.811
WP Error	6	0.87871	0.14645	19.74	0.000
Speed	1	0.00335	0.00335	0.45	0.504
Direction	1	0.01830	0.01830	2.47	0.121
Vehicle[HTC]*Speed	1	0.02407	0.02407	3.24	0.076
Vehicle[HTC]*Direction	1	0.00010	0.00010	0.01	0.910
Pressure[HTC]*Speed	1	0.01290	0.01290	1.74	0.191
Pressure[HTC]*Direction	1	0.00047	0.00047	0.06	0.802
Speed*Direction	1	0.03565	0.03565	4.81	0.032
Vehicle[HTC]*Pressure[HTC]*Speed	1	0.00037	0.00037	0.05	0.824
Vehicle[HTC]*Pressure[HTC]*Direction	1	0.00452	0.00452	0.61	0.438
Vehicle[HTC]*Speed*Direction	1	0.00139	0.00139	0.19	0.667
Pressure[HTC]*Speed*Direction	1	0.00446	0.00446	0.60	0.441
SP Error	73	0.54164	0.00742		
Total	95				

Split plot analysis

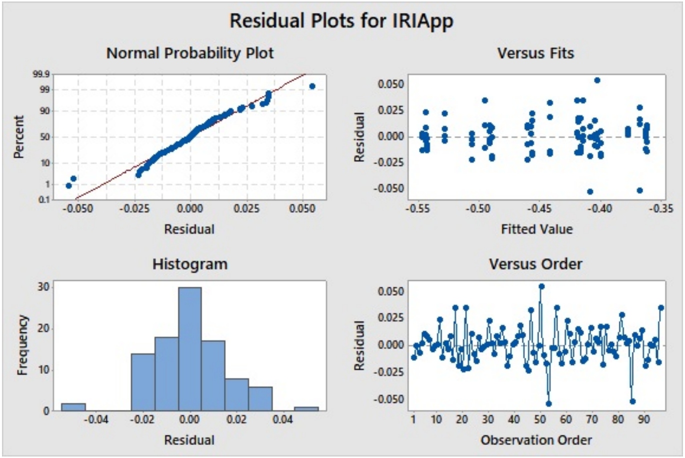


Figure: Split plot analysis residuals

Summary and conclusions

Summary and conclusions

We observe some linear relationship between the IRI measurements from the App and from the Rod and level, but we notice the measurements from the App are highly sensible to the different levels of the factors.

The mobile application is sensible to the car suspension system, and hence to many factors such pressure of wheels, mass of the vehicle, speed, etc.

There are some interactions between factors that seem to be important and need to be taken into account such as speed and up/down direction, and possibly vehicle and speed.

There are other factors that also affect the IRI measurements that need to be fixed such as location of the smartphone and number of people in the car.

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