MOBILE BASED ROUGHNESS MEASUREMENT

An economical road to pavement management

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EXECUTIVE SUMMARY

Current roughness data are obtained through expensive but accurate procedures. The alternative of a cellphone accelerometer-based measurement of IRI would be of relevance as it does not require expensive equipment or highly qualified personnel. However, the question of its practical accuracy is raised and within this accuracy what would its capabilities be for pavement management and planification.

To test the accuracy and repeatability of measurements, several runs under varying conditions were performed for Windsor Road on the 2nd November. It was found that, in accordance to other recent literature, the use of a sedan car yielded results closer to reality on all surfaces and conditions, when compared to an SUV.

After the use of the sedan, we found that results were repeatable and in accordance with profilometer roughness data. To do this we tried the software measuring roughness on Interstate Drive (PCC) and State Street (AC), both in Champaign, IL to confirm the accuracy on varying road surfaces, speed levels (15 and 30 mph) on the 7th of November.

Finally, its possible use as a decision support tool was assessed by contrasting the results obtained with current management practices with the city of Champaign. After meeting with officials from Champaign City Public Works (see Annex 7.2), a region was analyzed for PCI contrasting on November 29th the correlation between official measurements and IRI data with 3 different regression techniques was performed. In all cases an adequate correlation was found, where forest models yielded the best correlation. However, these are not sufficient to make a highly accurate prediction of PCI values (specially in mid-range values), rather its use is recommended for pre-screening of streets requiring in-depth studying. Also, its value could be increased dramatically by coupling the data with video, and could become a cheap, versatile tool for PMS. Also, the use of this tool could give consistent readings with a set of calibrated cars from Champaign City Public Works, yielding a reasonable degree of accuracy for road status control.

1 INTRODUCTION

Considering the increase in population, vehicles and demand for more pavements, the need for having a reliable pavement system is appreciated more than ever. Agencies must balance a budget considering the capital investment of building new pavements, as well as the maintenance, rehabilitation, and reconstruction of existing roads. Part of the maintenance cost comes from the data collection and quality measurements from existing pavements. During years, different approaches have been made by agencies to ease the process and make it more efficient such as implementation of Pavement Management System (PMS). PMS's are widely used by transportation agencies to evaluate and manage the condition of pavements in a cost-effective way[1].

One of the distresses inputs in PMSs is pavement roughness, which is often related to repair budget allocation. Roughness can be used to describe the condition and prioritizing maintenance, rehabilitation and reconstruction strategies for the road network[2]. Rougher roads lead to higher fuel consumption, which comprises 50% to 75% of total user costs[3]. Other cost associated with roughness is the depreciation of vehicle. About 30% of vehicle depreciation cost depend on vehicle mileage, which is also connected to the pavement roughness[4]. These user side costs plus agency maintenance costs, illustrate the importance of controlling pavement roughness. Roughness can be measured by the International Roughness Index (IRI). IRI is an index presenting the pavement roughness, ride quality and surface deviations. It is being used for evaluating pavement condition and need of maintenance, or for new pavement construction, to determine penalties or bonus payments based on smoothness. The IRI considers surface wavelengths between 0.5 to 50 meters and is based on the Golden Car model, which holds vehicle speed at 80 km/hour (50 mph) with known suspension properties and can be calculated by inputting collected data into this model. Vehicle vertical responses are aggregated then divided by the length traveled.

Laser profilometers can be used to collect IRI data from pavement surface. They can be mounted with other related equipment on a single van, known as Data Collection Vans (DCV) to obtain IRI data along the pavement system. Most transportation agencies use DCVs, to record the IRI data[5]

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[1] Flintsch, G., and McGhee, K. K. (2009). "Quality Management of Pavement Condition Data Collection." National Cooperative Highway Research Program: Transportation Research Board, NCHRP Synthesis 401.

[2] Greene, S., Akbarian, M., Ulm, F. J., & Gregory, J. (2013). Pavement roughness and fuel consumption. Concrete Sustainability Hub, Massachusetts Institute of Technology.

[3] Sinha, K. C., & Labi, S. (2011). Transportation decision making: Principles of project evaluation and programming. John Wiley & Sons.

[4] Haugodegard, T., Johansen, J. M., Bertelsen, D., & Gabestad, K. (1994). Norwegian Public Roads Administration: a complete pavement management system in operation. In CONFERENCE PROCEEDINGS 1 (Vol. 2).

[5] McGhee, K. K. (2004). "Automated Pavement Distress Collection Techniques." *National Cooperative Highway Research Program: Transportation Research Board,* NCHRP Synthesis 334.

(as described in NCHRP 334). Due to its cost some local engineering agencies may not be able or having difficulties to afford using this method (at the time of writing this report a company based in Champaign, Illinois informed $120/mile for the collection and analysis of IRI using DCV). On the other hand, due to its cost it is performed sporadically. To have an easy-to-use, less time taking, more up-to-date, and cost-efficient way of collecting IRI data, some cell phone apps have been developed and presented, aimed to collecting pavement roughness (IRI).

2 SOFTWARE REVIEW

In this project, a cell-phone-based software named RoadLabPro developed by SoftTeco and the World Bank was used to collect the pavement roughness (IRI values) at various locations (GPS coordinates). According to the software developer, this app uses algorithms for calculating road roughness on the International Roughness Index (IRI) based on the gyroscope and accelerometer data, and using cell phone GPS chip (latitude, longitude and altitude at sea level) to define user's location on the map[6]. Cell phone was mounted on a typical car cell phone mount sticker, in a complete vertical position, with no contact with any other obstacle, as it was pointed out in the software's instruction manual.

Through the app, there are a few options that can be changed in settings. Four options for type of car suspension, that user can choose from, including; Car Hard Suspension, Car Soft Suspension, SUV, and User Defined, in which user can define his own coefficients for car suspension system. App has default thresholds for categorizing road condition to very poor, poor, fair, good and very good base on the IRI range. These thresholds can be changed by user in both Paved and Unpaved options. To start recording, user must define a new project, then add the specification or description of a specific road/section he is taking to that project. User must define the pavement type (pave/unpaved). After defining the pavement, data collection can be started. App shows a live process of collecting data (roughness) to user, as well as the path user is driving, on the map, using GPS. It shows total distance, time, current speed, major bumps (possibly potholes), etc. some screen shots from the app as well as user manual are provided in Annex 7.1: Roadlabpro software manual.

In this project, three different sections of pavements in Champaign, IL were selected. Same cell phone and mount stick were used in all cases. At the first, using the software, data were collected with two different types of cars, SUV and Sedan. After performing repeatability analysis and data comparison between two cars, the most accurate one was selected. For next parts of the project, same car for measuring on different type of pavement structures (Asphalt Concrete and Portland Cement Concrete) were used. Repeatability and accuracy analysis were done in each case, between the collected IRI data from the app and Champaign City Public Work IRI data using DCVs.

[6] https://softteco.com/projects/roadlab

3 DATA ANALYSIS

As stated earlier, the main objective of this study was two-fold: To examine the accuracy of the mobile phone application and to test its repeatability (precision) as well. For the sake of testing the accuracy, data collected by the City of Champaign Public works were obtained for the comparison. These data were collected using state of the art technology (laser profilometer) and were, only for the sake of this study, considered as “true” or “error-free” data while the data collected in this study were considered as an estimate. As for precision evaluation, different measurements were done for the same street to check whether the application was able to produce the same results consecutively.

3.1 PRECISION ANALYSIS

If the application can get roughly the same results for the same settings, then it would be considered precise. For this, multiple drives were done on the various road links. Figure 1 shows an example of a repeated drive which is data obtained for Windsor Road in Urbana between Race Street and County Road 1400 E/South Philo Road using an SUV vehicle traveling at around 30 mph. This includes keeping the speed as close as possible to a target speed so that the comparison holds. Figure 1 shows the two IRI profiles obtained from the two trials. Neither the trend nor the values were repeatable. The value of the Root Mean Square Error (RMSE) and the absolute difference between the two means are 2.26 m\km and 2.13 m\km, respectively. This means that not only the individual corresponding values on the two curves are different, but also the mean measured values are almost as different from each other.

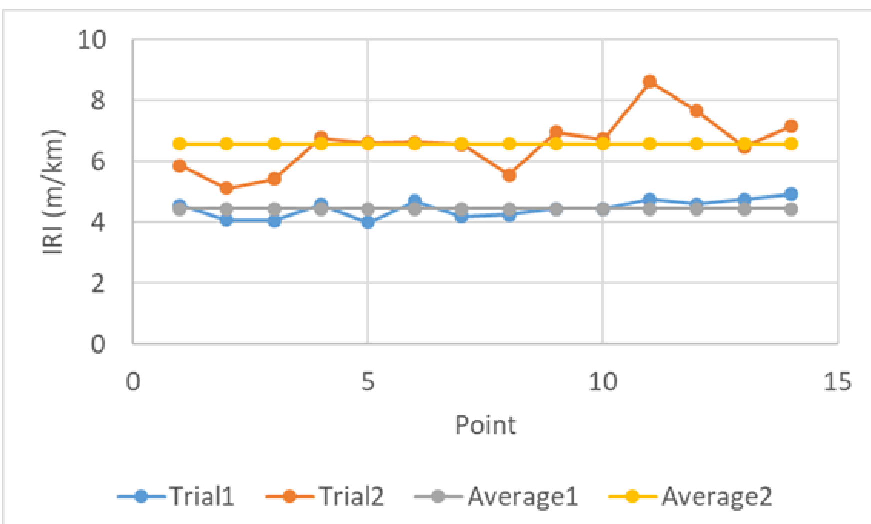

Figure 1: Precision Analysis of the SUV drive on Windsor Road

Table 1 shows RMSE and the absolute difference between the two averages for 6 repeated drives.

Suspension	Trial	Direction	Speed (mph)	Avg IRI (m/km)	RMSE (m/km)	Absolute Difference in Averages (m/km)	Pavement Type	Location
SUV	1	2	30	7.07	2.76	2.58	PCC	Windsor Road
SUV	2	2	30	4.49				
Sedan	1	N/A	30	2.54	0.13	0.02		
Sedan	2	N/A	30	2.56				
Sedan	1	N/A	15	2.17	0.06	0.04	PCC	Interstate Dr
Sedan	2	N/A	15	2.13				
Sedan	1	N/A	30	2.29	0.2	0.13		
Sedan	2	N/A	30	2.16				
Sedan	1	N/A	15	3.09	0.14	0.1	AC	State St
Sedan	2	N/A	15	2.99				
Sedan	1	N/A	30	2.98	0.14	0.02		
Sedan	2	N/A	30	2.96				

Table 1 Precision Analysis of Different Drives

As it can be seen, SUV results were very high (unreasonable) and non-repeatable. For this reason, the Sedan model was used to measure IRI and rate the accuracy of the app.

3.2 ACCURACY ANALYSIS

Comparisons were made between the collected data and the “true data”. A challenge faced was the difference in resolution between the two data sources. For the data obtained from the City of Champaign, the measurements were taken at a 100-ft interval. The collected data, in turn, was recorder in 100m intervals. To solve this issue, the average of three consecutive points for the true data was taken so that the comparison holds. The same analysis was done as in the previous section. Both RMSE and absolute difference of averages were calculated.

For the case shown in Figure 2, RMSE and absolute different of averages between Champaign City and the first trail are 1.35 m/km and 1.14 m/km, respectively. For the second trial, the respective values are 1.43 m/km and 1.04 m/km. Table 2 summarizes these values for all the trial done in different combinations.

Figure 2: Accuracy Analysis of the Drive on State Street

Suspension	Trial	Speed (mph)	Avg IRI (m/km)	True IRI (m/km)	RMSE (m/km)	Absolute Difference in Averages (k/km)	Pavement Type	Location
Sedan	1	15	2.99	4.13	1.43	1.14	AC	State St
	2	15	3.09		1.35	1.04	AC	
	1	30	2.98		1.29	1.13	AC	
	2	30	2.96		1.3	1.15	AC	
	1	15	2.17	1.92	0.41	0.21	PCC	Interstate Dr
	2	15	2.13		0.36	0.25	PCC	
	1	30	2.29		0.53	0.37	PCC	
	2	30	2.16		0.41	0.24	PCC	

Table 2 Accuracy Analysis of Different Drives

3.2.1 Analysis of Different Factors

As different factors were considered during this study (mainly vehicle type, speed, suspension setting, among others), the variability of accuracy and precision within across these values can be analyzed, which will bring many insights as to which testing configuration might be the best configuration to get accurate and repeatable results.

3.2.2 Vehicle Speed

Different drives were made mainly at two different speeds: 30 mph and 15 mph. Although mechanistically simulated models tend to have a higher speed (50 mph in the case of golden car model), a speed of more than 30 mph is usually hard to sustain in an urban environment. Also, 15 mph speed was picked to check if the software does better at lower speeds than at higher speeds. Real life may be very different from a perfected, simulated environment.

Due to the time limitation of this study, the sample size could not have been large enough for statistical inference to be done. For example, had there been a large-enough sample, it would have been insightful to test whether error values tend to get lower after the speed is increased/decreased (a one-way paired-t test). Table 3 shows a precision comparison between the two speeds. As can be noted, both speeds have high and low RMSE values without any hint of a significant difference based on speed. Furthermore, we noticed high and low values are for similar configurations which means speed by itself may not have a noticeable impact on repeatability.

Data Point	Speed (mph)	IRI (m/km)	True IRI (m/km)	RMSE (m/km)	RMSE/IRI
1	30	2.29	1.92	0.53	0.28
2		2.16		0.41	0.21
3		2.98	4.13	1.29	0.31
4		2.96		1.3	0.31
1	15	2.17	1.92	0.41	0.21
2		2.13		0.36	0.19
3		2.99	4.13	1.43	0.35
4		3.09		1.35	0.33

Table 3 Accuracy Analysis Categorized by Speed

Table 4 shows accuracy comparison between the two speeds. Again, it seems that other factors have a higher impact on the outputs than the speed. Seeing the sheer RMSE values, it might seem that the software has more accurate measurements of PCC than AC. However, looking into the normalized values (dividing the RMSE by true IRI value), the error values of the two pavement types are not far apart. Same can be said about the different speeds (no hint of significant difference).

Data Point	Pavement Type	RMSE (m/km)	True IRI (m/km)	RMSE/True IRI
1	AC	1.43	4.13	0.35
2		1.35		0.33
3		1.29		0.31
4		1.3		0.31
1	PCC	0.41	1.92	0.21
2		0.36		0.19
3		0.53		0.28
4		0.41		0.21

Table 4 Accuracy Analysis Categorized by Pavement Type

3.2.3 Pavement Type

As both AC and PCC pavements were driven on, accuracy and repeatability were analyzed for both types of pavements. The same analysis was tried with pavement type without seeing a noticeable difference. However, the main reason causing differences when they happen is car type. When an SUV vehicle was used, results had poor repeatability and gave much higher results than when the sedan car was used (which gave accurate results in other tests). This comes in line with literature where SUV's are not generally used to take IRI measurements because of their large height over the ground and because of their suspension system which is believed to add more vibrations.

3.3 RESULTS DISCUSSION

First, a sedan vehicle showed to have better results and accuracy than a SUV. Overall accuracy is satisfactory but could be improved, further testing could find other factors that improve accuracy; nevertheless the results were found to be repeatable. Further work is needed in the future to find out whether regression analysis can be used to enhance the accuracy of the data. Also bigger sampling would be required to unveil correlations which were considered random variations in this study.

4 PRACTICAL EVALUATION AS DECISION SUPPORT TOOL

The following chapter describes the analysis, methodology, and results obtained for the purpose of using the mobile roughness app collector as a tool to make better decisions in the low volume street management of Champaign city

4.1 INTRODUCTION

During the conversations with Champaign City public works (see Annex 7.2: Champaign City Public Works Meeting) the relevance of the app was discussed considering the high cost of roughness measurements with laser profilometers. A high volume of the calls regarding maintenance requests from local citizens are for residential streets, for which a detailed roughness measurement is not cost-effective or simply not warranted within budget constraints.

4.2 CURRENT PRACTICES

4.2.1 PCI Ratings

PCI (Pavement Condition Index) is a method for rating the condition of streets based on inspection and observation of the surface[7]. It is a score within a 0-100 scale, with 0 being the worst condition and 100 being "pristine".

PCI	Grade	Condition
81-100	A	Excellent
61-80	B	Good
41-60	C	Fair
21-40	D	Poor
0-20	F	Failed

Table 5: Champaign City condition ratings for PCI

[7] Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys, D6433 – 16, ASTM International, (2016)

PCI is a starting point for identifying what streets need work and select among possible candidates. Further evaluation and investigation are needed to determine what treatments are needed in each case. Scheduling, data management system, and procedures are outlined in Annex 7.2. PCI collection is done every other year.

4.3 METHODOLOGY

PCI is correlated with the ride quality experienced by users, therefore a pavement management prioritization guided by PCI is aiming to produce a better service for users. Roughness also correlates to user ride quality but does not capture the range of distresses that are conducted in a PCI analysis. Nevertheless, there are previous works attempting to relate both measures[8] [9]. For this report, a section of the pavement network system rich in PCI data was selected to contrast results obtained via the app and current PCI measurements.

4.3.1 Selection

The roads selected were delimited by Kirby Ave., Mattis Ave, John St. and Prospect Ave. The streets within this region have a PCI averaging in 57, with a maximum of 99 (Sangamon Dr.) and a minimum of 14 (Daniel St.). This area is chosen for having low traffic and a representative distribution of PCI values.

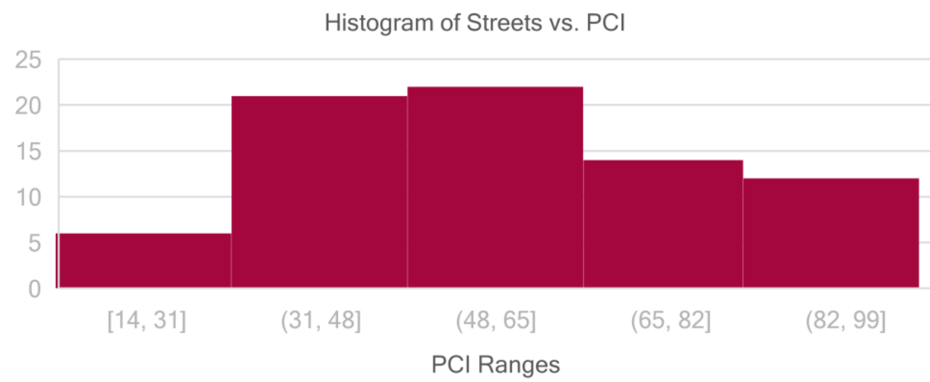

Figure 3: Count of number of streets for PCI ranges

4.3.2 Data Collection

The results obtained are presented below displayed in Google Earth. The color intensity represents the IRI range level obtained (Poor, Fair, Good, etc.) An average speed of 30mph was kept during the measurements around the neighborhood.

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[8] Lin, Jyh-Dong & Hsiao, Liang-Hao & Student, Graduate. (2003). Correlation analysis between international roughness index (IRI) and pavement distress by neural network.

[9] Dewan, Shameem & Smith, Roger. (2002). Estimating International Roughness Index from Pavement Distresses to Calculate Vehicle Operating Costs for the San Francisco Bay Area. Transportation Research Record. 1816. 65-72. 10.3141/1816-08.

Figure 4: Results obtained for the area of interest

4.3.3 Model Fitting

In order to assess the capabilities of a model that predicts PCI through IRI data, we propose a linear model, a k nearest neighbor model, and a random forest model. The accuracy levels obtained are summarized below and details are provided in the annex:

Method	RMSE	R squared	Model Parameters
Linear Regression	18.07	0.236	a = 90.56, m = -10.44
Nearest Neighbor	18.82	0.237	K = 9
Random Forest	13.77	0.575	M_t=19

Table 6: Model results for PCI vs IRI

We observe that the random forest model draws on more data than the other two models, which gives it the better fit. In all cases a correct correlation was evidenced, with a stronger value on very good or very bad values of PCI.

4.4 DISCUSSION

The literature shows that roughness is a component in the PCI calculation, where some agencies give different weights to the value of roughness as the “ride quality”. The PCI, however, is a more detailed measure considering the actual distresses evidenced in the pavement. Although these are captured to an extent by the IRI measurement, they do not replace the PCI traditional collection methodology. However, the strong correlation between both measurements indicates that a fast IRI computation could be a good economical proxy measurement of PCI, even more so considering the possible acquisition of visual data along with the recording of roughness.

An extension of the model with other data sources parallel to a calibration by measuring some major roads could be the most economical and valuable methodology to enhance Champaign's pavement management system.

5 CONCLUSIONS

5.1 SOFTWARE CAPABILITIES AND SHORTCOMINGS

The RoadLabPro app can be a cost-effective way of measuring pavement roughness. It measures IRI in 100-m intervals, showing major bumps, information about speed, traveled distance and path in GIS format. The app is user-friendly and can be used in daily commutes. The app can sync the collected data to Dropbox, Google Drive or One Drive, which makes it easier to use. However, it is not clear that how it transforms the collected data to IRI, or what its processing algorithm in dealing with variables is. The app is missing some options such as suspension; for example, all SUV cars are defined in the same category, while this could have been divided to more categories such as weight, size or model of the car. Poor results were obtained for SUV, it might be the suspension settings that was considered for SUV as a general definition, or the algorithm that app uses by changing the suspension type, which are unknown.

The app is intuitive to use, there were problems in extracting data, it could name the files shorter and easier to understand. Every time we started to the collect data the first measurements were missing GPS coordinates; it takes a while for the software to find the location. Sometimes software does not record the pavement roughness and the driver is not warned, hence it requires a mechanism to alert the driver without having to be distracted from driving.

5.2 SOFTWARE ACCURACY

As discussed in the data analysis section, the software is generally precise and accurate. However, it is not a perfect replacement for a full laser profilometer measurement. For example, important assets like interstate highway pavements, which may be worth hundreds of millions of dollars and small decisions may cost millions of dollars, this software cannot be used with its current performance. The software averages measurements roughly every 100 meters which, if decreased, could help increase accuracy.

It was found that speed does not have a noticeable impact on accuracy in the range of 15-30 mph (the normalized RMSE was 0.28 for both speeds). However, driving at higher speeds is not practical in urban areas mainly due to urban speed limits. The measured data showed to be more accurate using a sedan vehicle rather than a SUV. In the case of SUV, IRI values were much higher than that of the sedan measurements and were also barely repeatable. Sedan values showed to be accurate and repeatable. Pavement type did not have much impact on accuracy as both tested AC and PCC pavements gave close values of normalized error. Normalized RMSE was found to be 0.33 for AC and 0.22 for PCC, within a limited sample size.

5.3 FURTHER TESTING

Other useful variables to test would be tire pressure, although the hardness of the suspension is considered, within a suspension type the tire pressure could change measurements through time.

The location of the accelerometer is not defined in the software, where dashboard or windshield configurations could have varying degrees of impact. The type of holder used as well as the transversal position in the car could also have relevant implications for the measurements.

The type of driving patterns could have an effect and having a consistent methodology of how to drive in a street with potholes would be needed to make consistent readings. As it stands today, there is room for driver affectation of the IRI values obtained.

In this study two types of cars were analyzed, SUV and a sedan. As discussed previously, big differences were found between each type and having more specific settings customizations could be useful.

5.4 TOOL FOR DECISION MAKING

The overall effectiveness of the app as a decision support tool is acceptable, however for a useful implementation the points mentioned above should be considered, plus some application specific improvements:

- Coupling of the IRI data with other information sources (video imagery, structural layers, etc.) as well as the use of higher resolution accelerometer (not aggregated) data could give better raw results. Also, it would help with the detection of potholes or localized defects.
- The correlation to PCI is existent but depends widely on the range of PCI analyzed. Further region analysis could help stabilize the results.
- Considering the use of roughness by itself as a better measurement of user experience could be a better way to prioritize. This combined with traffic counts could by itself be a good hierarchization of works. The advantage of this software over other measures as PCI is that this software gives an objective physically measured attribute rather than a subjective measurement, at a low cost.
- The method could be used as a pre-screening method of the streets, were the results obtained would signal which streets require further evaluation and merit a PCI measurement.
- Crowdsource data for roughness looks unviable due to the varying degree of measurements that can be obtained, a reasonable work scheme would be having the city running routine drives with calibrated vehicles.

6 REFERENCES

1. Flintsch, G., and McGhee, K. K. (2009). "Quality Management of Pavement Condition Data Collection." National Cooperative Highway Research Program: Transportation Research Board, NCHRP Synthesis 401.

2. Greene, S., Akbarian, M., Ulm, F. J., & Gregory, J. (2013). Pavement roughness and fuel consumption. Concrete Sustainability Hub, Massachusetts Institute of Technology.

3. Sinha, K. C., & Labi, S. (2011). Transportation decision making: Principles of project evaluation and programming. John Wiley & Sons.

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6. Roadlab Pro Manual, (2009), SoftEco, site: https://softteco.com/projects/roadlab

7. Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys, D6433 – 16, ASTM International, (2016)

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7 ANNEXES

7.1 ROADLABPRO SOFTWARE MANUAL

"RoadLab Pro"
App Setup and Data Collection Guide

The RoadLab Pro app estimates the road roughness based on kinematic and GPS sensors in smartphones. Please follow the guidelines here in order to get more reliable estimation of road roughness and interpretation of information on the screen.

1. The cellphone should be mounted securely on the windshield (preferred) or flat and firm dashboard (less preferred). The phone should be mounted in a vertical position.
2. It is important to select proper vehicle suspension type. Note the suspension type also reflects the influence of cellphone cradle: a wobbling cradle could increase the variability of the acceleration measured. The hard-medium type is suitable for most general passenger cars while SUV can be selected separately as well.
3. It is a good practice to define "project" and "road (road link)" name first.
4. Link with personal or institute Dropbox or Google Drive account to allow data to be easily uploaded to cloud.
5. Data collection interface displays several key parameters.
    a. The dynamic plot in the middle shows the time series plot of vertical acceleration, which is directly related to road roughness.
    b. The color coded "roughness in the past 100 meters" provides a visual illustration of road roughness.
        i. It displays the roughness in the past 100 meters so there is a time lag: it reflects the past 100 meters, NOT the current driving section.
        ii. The roughness range is
            1. IRI<2: Excellent
            2. 2<IRI<4: Good
            3. 4<IRI<6: Fair
            4. IRI>6: Poor

Note this range is for visual display purpose. The output table contains the measured IRI values.

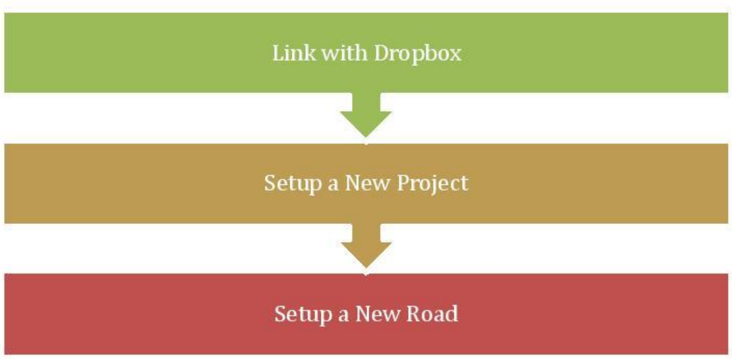


Figure 1 Setup Dropbox Pro

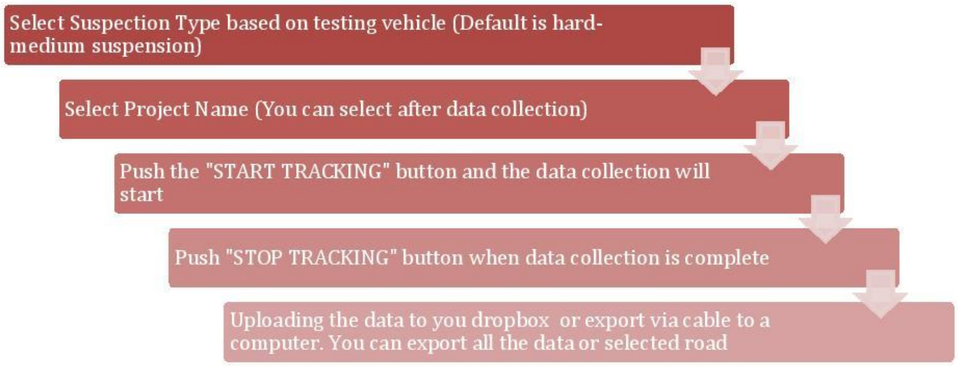


Figure 2 Data Collection Procedure

- After clicking "Start" button, the IRI data collection will start when speed is higher than 15 km per hour (for better accuracy) while GPS coordinates are recorded all the time regardless of speed.
- If you like to monitor the data collection process, select "Screen Always On" button in the "Setting" menu though this is more likely to consume battery faster.
- There is a tab button ("+" sign) on the upper right corner of the data collection screen. You can add tags if needed.

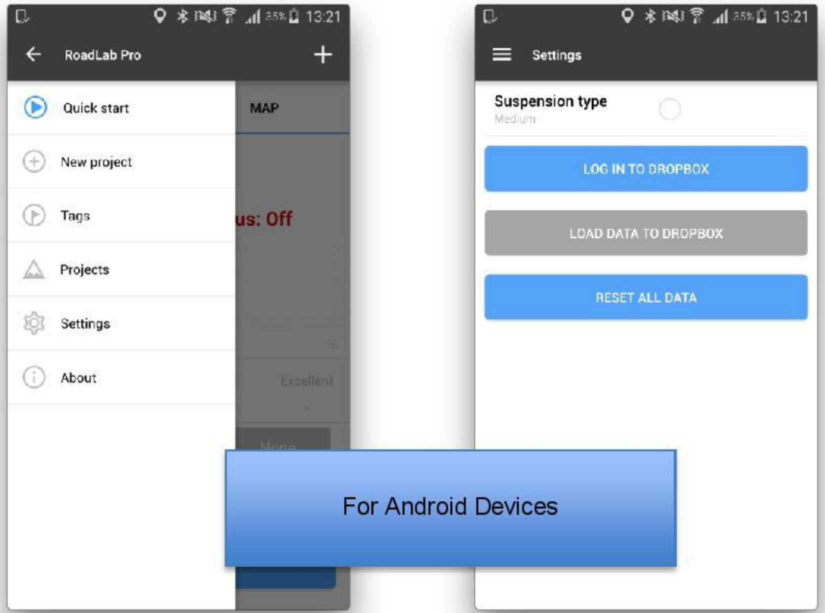
Warning: Driver should focus on driving at all time. Distracted driving can lead to traffic accidents. There is no need for drivers to engage in app operation while driving. Any app related operation during driving (for example adding a tag) should be done by a passenger.

1. First time application launch

When user installs the application for the first time, the application will show the Splash screen and tutorial.
The settings are set by default:

- "Suspension Type" – Hard-Medium;
- "Always On Screen" – Off;
- "Dropbox account" - not set.

The recent Project and recent Road (road link) is not set.


13:21
RoadLab Pro
Quick start
MAP
New project
Tags
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Projects
Settings
About
Excellent
13:21
Settings
Suspension type
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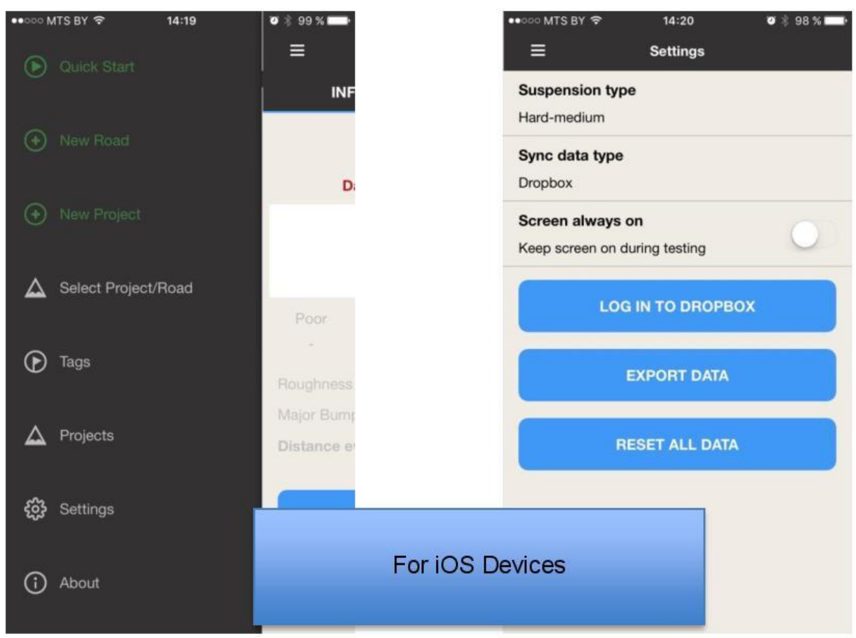
RESET ALL DATA
For Android Devices


MTS BY
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99 %
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New Road
New Project
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Poor
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98 %
Settings
Suspension type
Hard-medium
Sync data type
Dropbox
Screen always on
Keep screen on during testing
LOG IN TO DROPBOX
EXPORT DATA
RESET ALL DATA
For iOS Devices

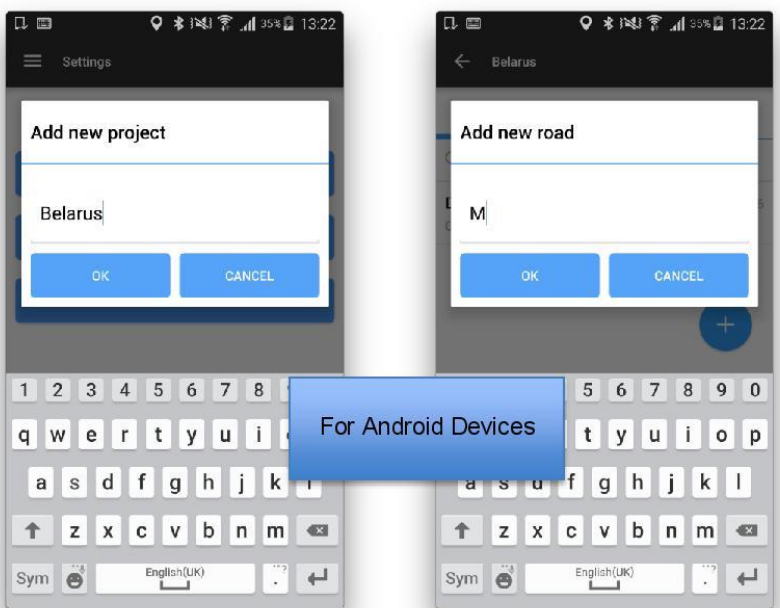
The menu consists of standard menu items:

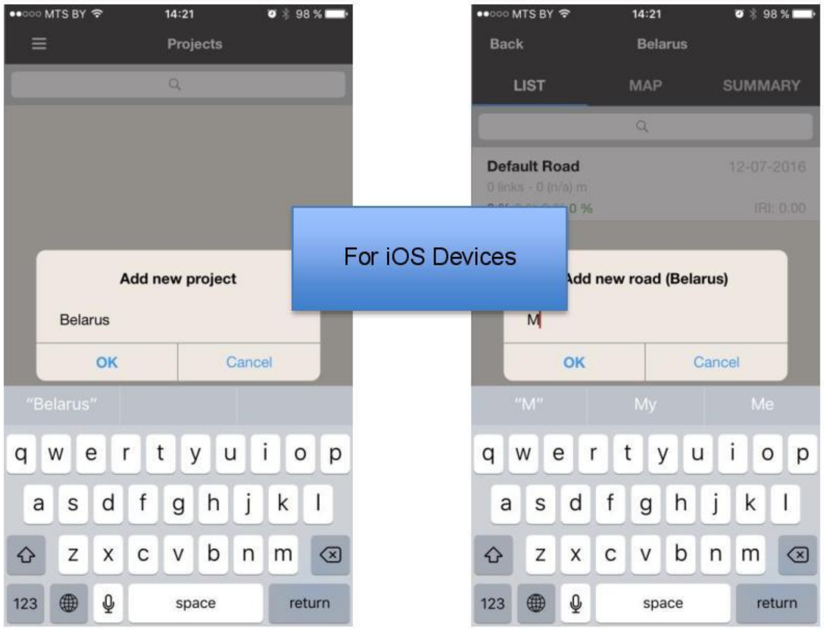
- Quick Start - to start measurement process, the application opens the Main screen and user is able to immediately start data collection, user will be able to create a Project and Road later; The Quick Start menu will be turned off after first use.
- New Project - to create a new Project, new Road and start measurement process;
- New Tag - to tag the recent geo-location;
- Projects - to manage all the data collected by the application;
- Settings - to manage application settings;
- About - screen to show some information about the application.

2. “Quick Start” and “New Project”

User is able to start immediately data collection procedure by tapping the “Quick Start” button. The application opens the Measurement screen and user is able to start Measurement process. “New Project” menu item helps users to set data structure for new projects. The application opens the Projects screen where user is able to create a new project and the new road link.

The new Project and new Road become the recent Project and recent Road after creation. Their titles are put as the first item of the Slide Panel menu.
Tapping on the first item opens the Main screen and starts the data collection.

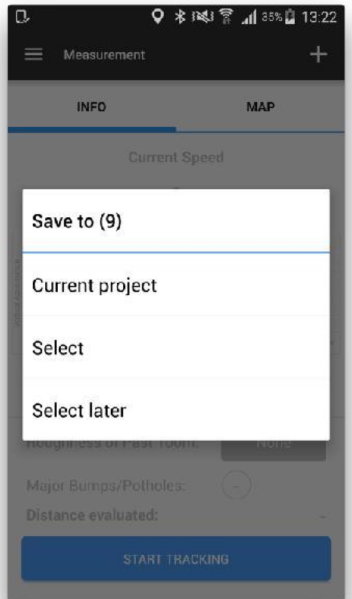




3. Measurement screen

Data collection process can be displayed either on Info tab or on the Map tab:

- Info tab contains area with acceleration graph, icons to display the device orientation state and the GPS status, some technical data related to recent measurement process and the button to start/stop measurement;
- Map tab displays the recent Measurement data on the Google Maps screen: the road intervals, road bumps and the tags of the recent measurement are displayed there.



Both tabs share common UI elements:

- "+" icon - adds a new Tag;
- Device orientation indicator - shows current position status of the device; "Red" means the phone is not securely fixed and data collection will not start.
- GPS accuracy indicator - has two statuses: "red" (no GPS signal) or "green" (good);
- "Start tracking button" - initiates new session of collecting. When process starts, the text on the button switches to "Stop tracking";
- Some info relevant to current measurement is displayed along with graph (map).

When "Stop tracking" button is tapped, "Save to…" action sheet is displayed. It allows 10 seconds to select a destination. The "Save to (9)" bar will show time left for selection. There are following possibilities for saving measurement:

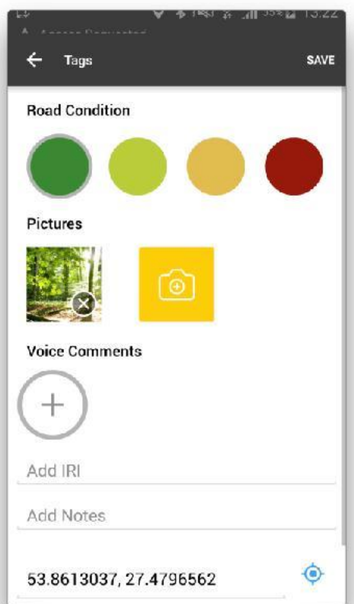
- "Save to current project" - saves data into project set to "Current";
- "Select" - opens screen with the list of projects. User can either select one of the projects in the list or create a new project. After that screen, the screen for selecting road is displayed, where user can select existing roads or create a new road;
- "Select later" - saves data to "Unsorted" project. User can access and replace saved data later in "Projects" section.

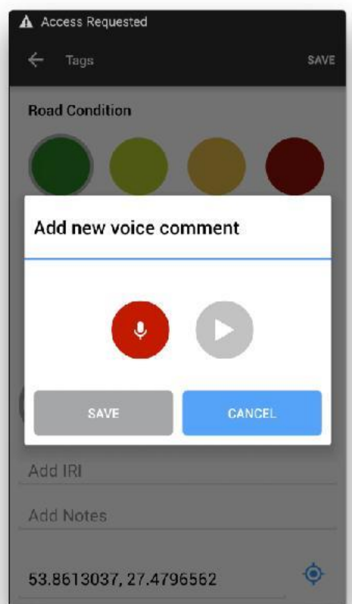
4. Adding a new tag

On tapping "+" icon on "Measurement" screen, a new tag on current location is stored and "Tag was successfully added" dialog is displayed. Users can add additional details to this tag immediately or skip and add details later (saved tags are displayed on the "Intervals" screen).

"Add tag details" screen allows adding following information about tag:

- "Road condition" – to allow road engineers manually enter visually observed road conditions (excellent good, fair, poor)
- "Pictures" - add pictures from device or take new pictures;
- "Voice comments" - record audio comments to the tag;
- "Add IRI" – to allow road engineers manually enter visually estimated IRI number;
- "Notes" - add additional text notes.





5. Manage data collected

User is able to manage data collected from the app using “Projects” menu. There are four levels of data:

1) **Project** - the top level of the data structure.

Usually this is at the “country” or “region” level. For example - “Belarus, Minsk region”, “Poland, Warszaw” and etc. The Project contains one and more Roads entities. User is able to create/read/update/delete any Project in the application data.

2) **Road** - the “road” level of the data structure.

Examples “M1 Minsk-Brest”, “E95 - May 2016” and etc. The Road contains one and more Measurement entities. User is able to create/read/update/delete any Road in the application data.

3) **Measurement** - the “distance” structure level.

This is the list of 100-meters road intervals. Measurement entity is created automatically when the measurement process starts and then fills with the 100-meter intervals. When the measurement stops, the Measurement entity is closed. User is able to create (by tapping START button)/read/update/delete any Measurement in the application data.

4) **Road Interval** - the basic level of the data.

Usually this is approximately 100 meter interval (note due to GPS measurement precision, the distance is not exactly 100 meters in most cases). Contains geo-tag (latt, long) of the start and finish points, IRI and some additional technical data (id, date and time).

5) **Road Bump** - the bump event on the road.

This records bumps that were tracked during the measurement process. It contains the geo-tag of the bump, maximum value of the standard deviation of the acceleration vector and some technical information.

6) **Tag** - additional data structure to store important notes that user takes during the road evaluation process. This element could be the part of road infrastructure assessment or could be any other independent data element.
   - if the Tag is recorded during the measurement process and the recent Project and recent Road values are set - the tag is connected to this recent Road entity;
   - In other cases the Tag is independent and does not contain any link to any Road.

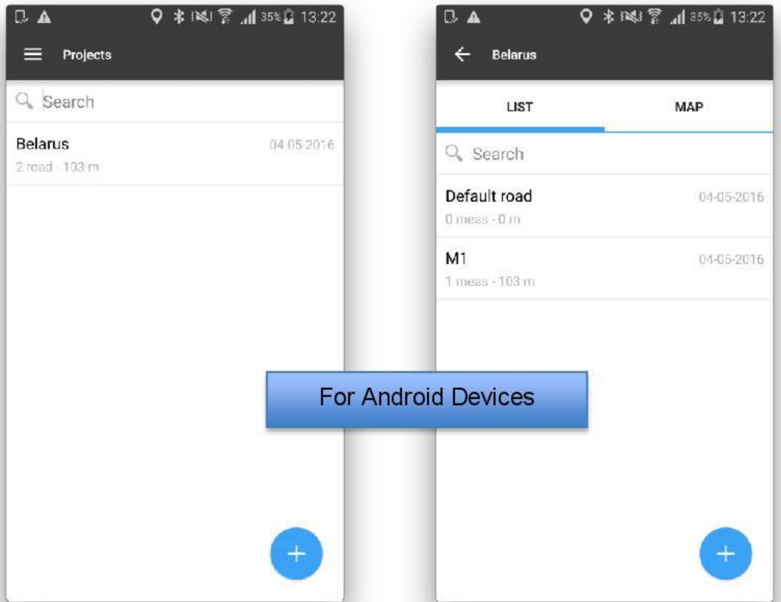
The tag can contain the data that are entered and managed by user:

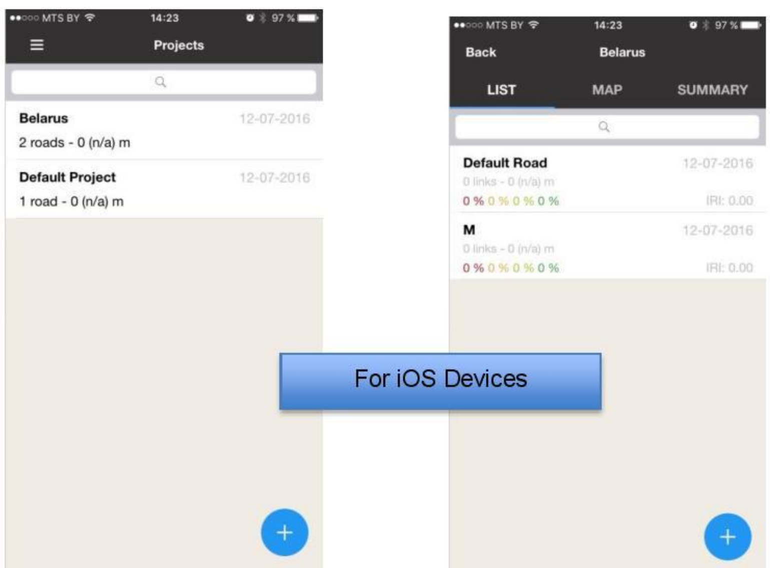
- Road evaluation (poor, moderate, good, excellent);
- Road evaluation - number from 0.0 to 100.0
- Photos;
- Voice message (audio file);
- Text notes;

… and technical data:

- Date and time;
- Unique identification.

User will be able to navigate through the Project - Road - Measurement - Road Interval / Road Bump / Tag

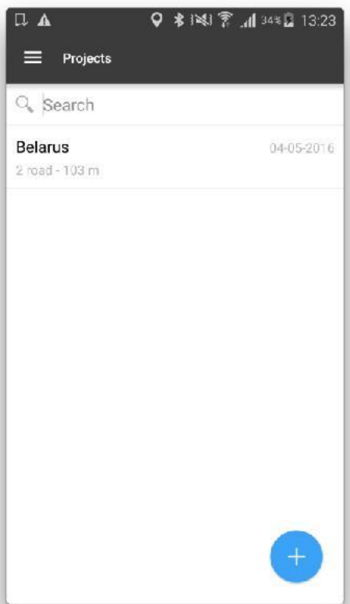

13:22
Projects
Search
Belarus
04-05-2016
2 road - 103 m
Belarus
LIST
MAP
Search
Default road
04-05-2016
0 meas - 0 m
M1
04-05-2016
1 meas - 103 m
For Android Devices

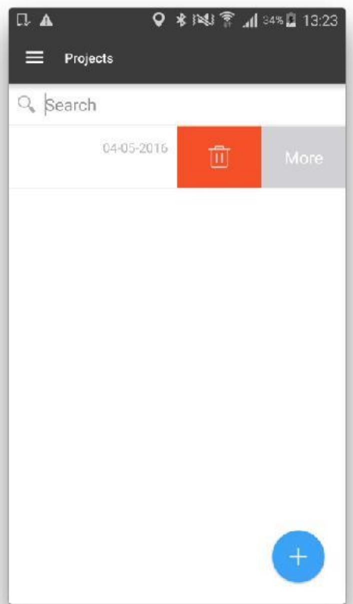

MTS BY
14:23
97 %
Projects
Belarus
12-07-2016
2 roads - 0 (n/a) m
Default Project
12-07-2016
1 road - 0 (n/a) m
Back
Belarus
LIST
MAP
SUMMARY
Default Road
12-07-2016
0 links - 0 (n/a) m
0 % 0 % 0 % 0 %
IRI: 0.00
M
12-07-2016
0 links - 0 (n/a) m
0 % 0 % 0 % 0 %
IRI: 0.00
For iOS Devices

User is able to manage the Project/Road/Measurement/Interval/Bump/Tag using the standard CRUD operations:

- Create
- Read
- Update
- Delete

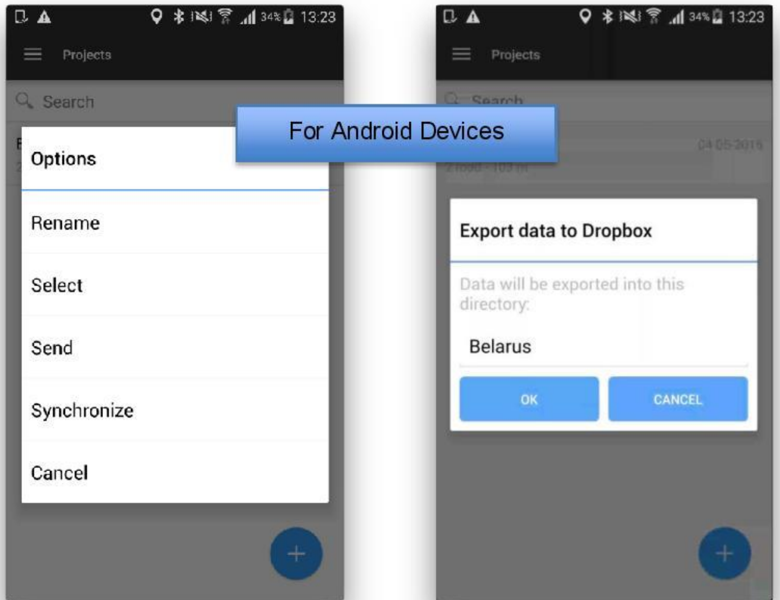
All these operations could be done using native iOS and Android UI elements.

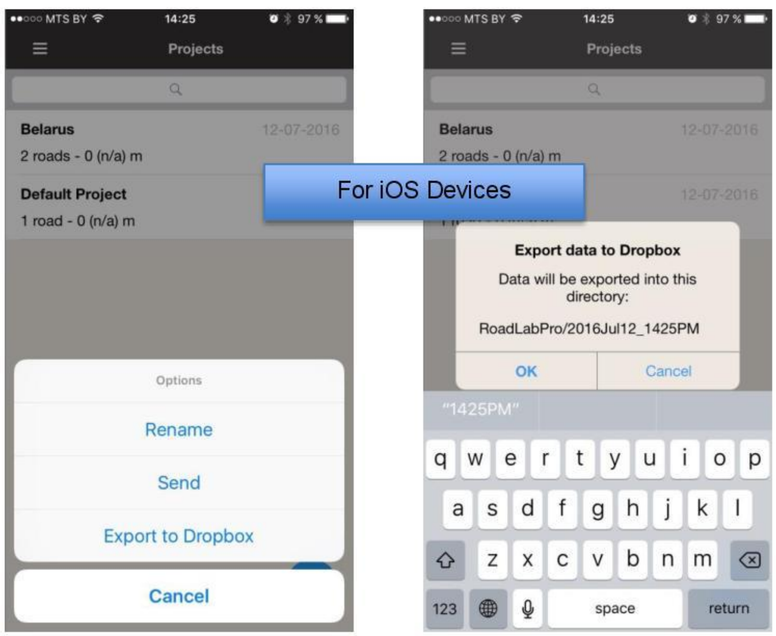




The standard “swipe-to-left” gesture functionality is implemented. User is able to delete the selected entity by tapping DELETE button or tap MORE button and choose one of the following operations:

- Rename;
- Select (to select as the recent);
- Send (send all the data via email);
- Synchronize (upload the data to Dropbox or Google Drive);


For Android Devices
13:23
Projects
Search
Options
Rename
Select
Send
Synchronize
Cancel
Export data to Dropbox
Data will be exported into this directory:
Belarus
OK
CANCEL


For iOS Devices
MTS BY
14:25
97 %
Projects
Belarus
12-07-2016
2 roads - 0 (n/a) m
Default Project
1 road - 0 (n/a) m
Options
Rename
Send
Export to Dropbox
Cancel
Export data to Dropbox
Data will be exported into this directory:
RoadLabPro/2016Jul12_1425PM
OK
Cancel
"1425PM"
space
return

6. Export data structure

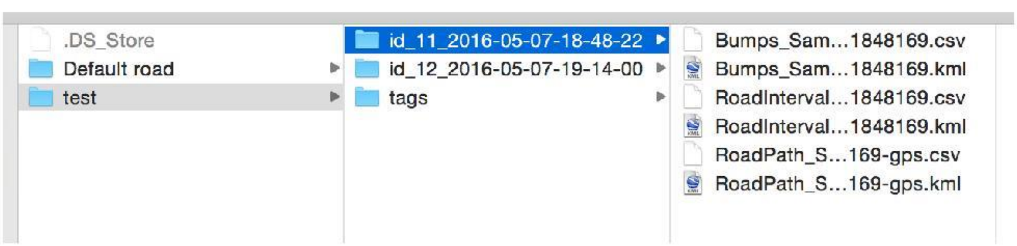
The exporting functionality is implemented on the file system level. This means that all the data are presented in the files.
There are two types of export:

- Export via email;
- Export via Dropbox or Google Drive

The export via email archives (zips) all the files of selected FOLDER or ROAD.
The export via Dropbox/Google Drive uploads all the files to the Dropbox/Google Drive directly.

Following is a brief description of the file structure:

- The high level of the data is the PROJECT entity. This is the highest level of folders which contain the all projects that are exported from the device. If there is no project set on the device, this folder will contain the “Default project” folder. This folder is the storage of all the data not set to any project of any road.
- Each PROJECT folder contains the following elements:
  - “Default road” – the road for all data for unset Road entity;
  - The list of Roads in the project.
- Each ROAD folder contains the following elements:
  - TAGs folder – the folder where all tags related to this Road are stored;
  - The list of folders with the MEASUREMENTS. This folder has very specific filename: “id_11_2016-05-07-18-48-22”, where “11” is the number of measurement, “2016-05-07” – date of creation, “18-48-22” – time of creation.
- Each MEASUREMENT contains of the following elements:
  - The Bumps files of the measurement (csv and kml formats) – the file where all the bumps detected during the measurement are stored;
  - Road Intervals of the measurement (csv and kml formats) – the file where all the evaluated road intervals are stored;
  - Road Path of the measurement (csv and kml formats) – the file where all GPS coordinates are stored no matter the vehicle speed and can be used for road network mapping.



6.1 Road Interval csv file structure

Parameter	Example	Description
time	18:48:46 2016-May-07	The date and time when the measurement of the evaluated road interval starts
speed	36.13	The average speed (km/hour) for the road interval
category	EXCELLENT	The category of the road interval (excellent, good, fair, poor)
start_lat	53.87774263	The start point: latitude
start_lon	27.56801968	The start point: longitude
end_lat	53.87686959	The finish point: latitude
end_lon	27.56820651	The finish point: longitude
Is_fixed	true	The device position true –vertical, false horizontal
iri	1.65	The calculated IRI of the interval
distance	112.22	The distance of the road interval

6.2 Bump csv file structure

Parameter	Example	Description
time	18:53:46 2016-May-07	The date and time when the bump was detected
speed	18.17	The average speed (km/hour) for the road interval
lat	53.84868593	Geo-tag: latitude
lon	27.57645522	Geo-tag: longitude
Ax	-0.41778821	The vertical acceleration vector of the bump X
Ay	6.76960516	The vertical acceleration vector of the bump Y
Az	2.52109432	The vertical acceleration vector of the bump Z
Is_fixed	true	The device position true –vertical, false horizontal

7.2 CHAMPAIGN CITY PUBLIC WORKS MEETING

A meeting was conducted with Champaign City Public Works on the 27th of October to determine possible uses of the mobile measurement of IRI. The following items were discussed:

7.2.1 Scheduling

Pavement condition ratings are conducted every other year and reported to Council for the consideration of each year's contract, which includes information on the cost and scope of work provided.

The current City practice is to conduct the inspections every other year. While some streets do not change much over a year or two (typically those in better condition) others may change significantly depending on the amount of traffic, the current condition, drainage issues, condition of the sub base, the type of traffic. Streets in the middle and lower half of the PCI scale are those that may change significantly over a shorter period of time. Updating the information on a regular basis helps track the condition of current pavement conditions and develop better projections for future road conditions to aid in work planning and budgeting of maintenance dollars.

7.2.2 Prioritization system

Every year, the Public Works Department updates a three-year plan for contract street maintenance work. The first year of that plan determines the work locations for the next construction season. Year 2 and 3 outline the current thinking on locations for year 2 and 3 but are subject to the condition and/or maintenance demand for other streets.

Work locations for the annual concrete street and asphalt street maintenance contracts are selected based on several key factors including the pavement condition ratings, recurring maintenance issues, and citizen input.

The pavement management database is used in the development of the three-year work plan. The database can be used to create maps displaying PCI ranges in a color-coded map format to allow for identification of streets and neighborhoods with low ratings for additional consideration. Those streets are compared to Operations division maintenance requirements and there are general discussions with Public Works Operations staff regarding streets posing maintenance challenges and/or those consuming a lot of work hours to maintain.

Current city PCI conditions are summarized in the IDEA (Interactive Data Exchange Application) module by APTech, a screenshot is provided below:

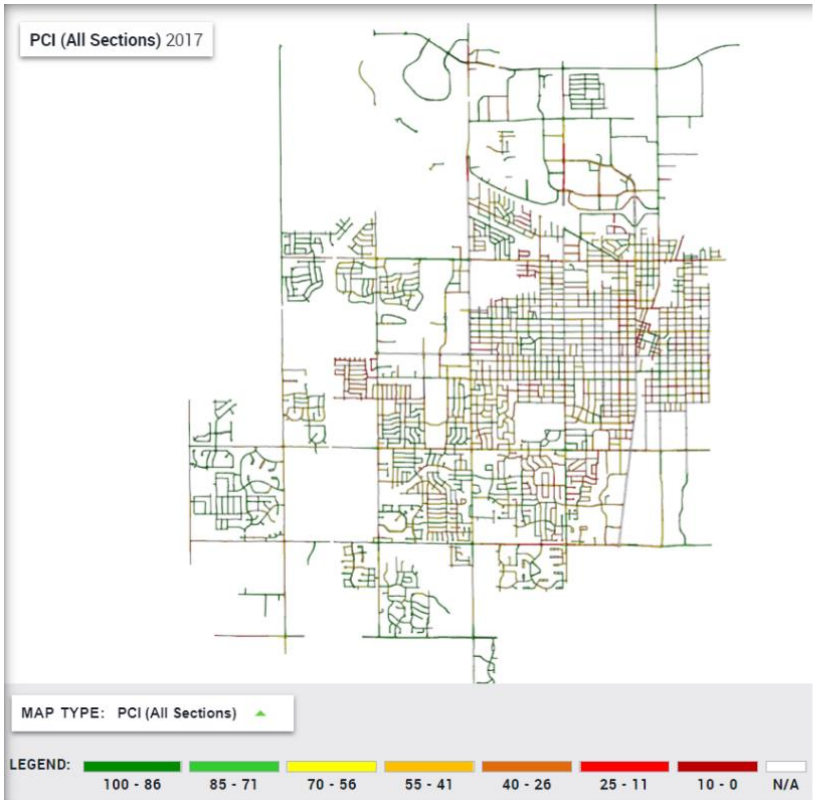


Figure 5: APtech IDEA network view for PCI

7.2.3 PCI and Roughness considerations

As a public entity Champaign City Public Works receives phonecalls from citizens requiring maintenance of certain roads. It is understood that the main thing a driver notices about a street is ride quality, and in general, this corresponds to PCI. The lower the PCI value of a street, the more likely the ride quality is rougher. Streets of either type with a sub-20 PCI rating would have vertical distresses that result in bumps, dips, and other things contributing to a rougher riding experience for the driver.

For a concrete pavement, the types of distresses would result in large cracks and failures resulting in the concrete panels being broken up into smaller pieces – the more and smaller the pieces the greater the distress. There would also be settlement of some of the panel pieces. Higher PCI pavements may have small localized areas exhibiting this (which van typically be corrected by replacing the localized area) while the 0-20 PCI pavement segments would have much larger overall areas (and percentage of total area) of this type of distress.

For and asphalt pavement, the main type of distress would be fatigue cracking, which are closely spaces cracks typically in the wheel paths indicating the roadway is struggling to handle the loading from vehicles. This ends up resulting in potholes and patches of the asphalt which are typically visible.

The city showed interest in the possibility of having an economical analysis of roughness for residential streets, were roughness is not typically measured. (Only measured for main arterials)

7.3 MODEL FITTING

7.3.1 Input data

The data collected for the section defined is imported below

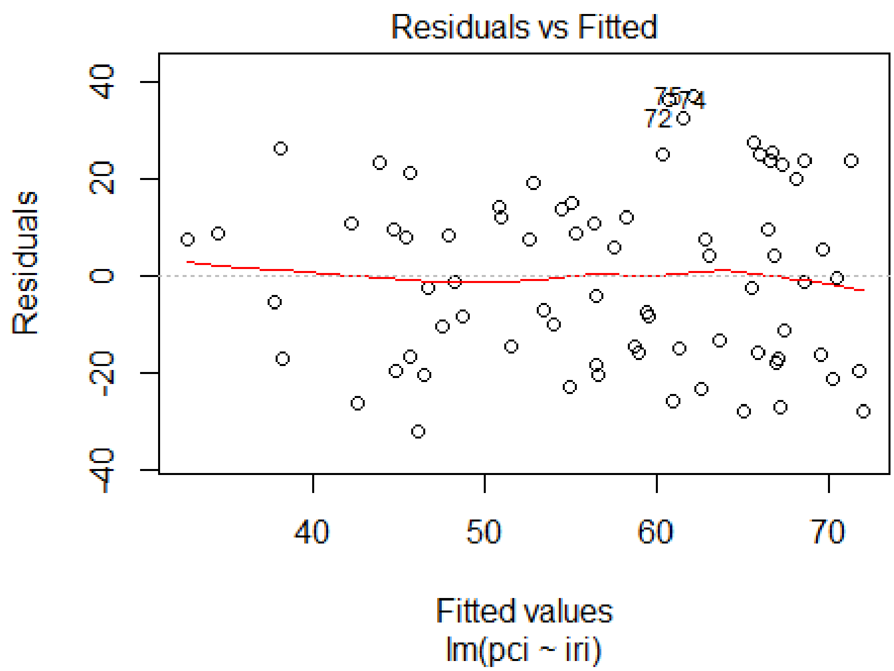
```
data=read_csv(file = "C:/Users/jpb6/OneDrive - University of Illinois - Urbana/Fal
l 2019/CEE 508 - Pavement Evaluation and Rehabilitation/Term Project/DATA/irivspci
2.csv",col_names = T)
data=as_tibble(data)
```

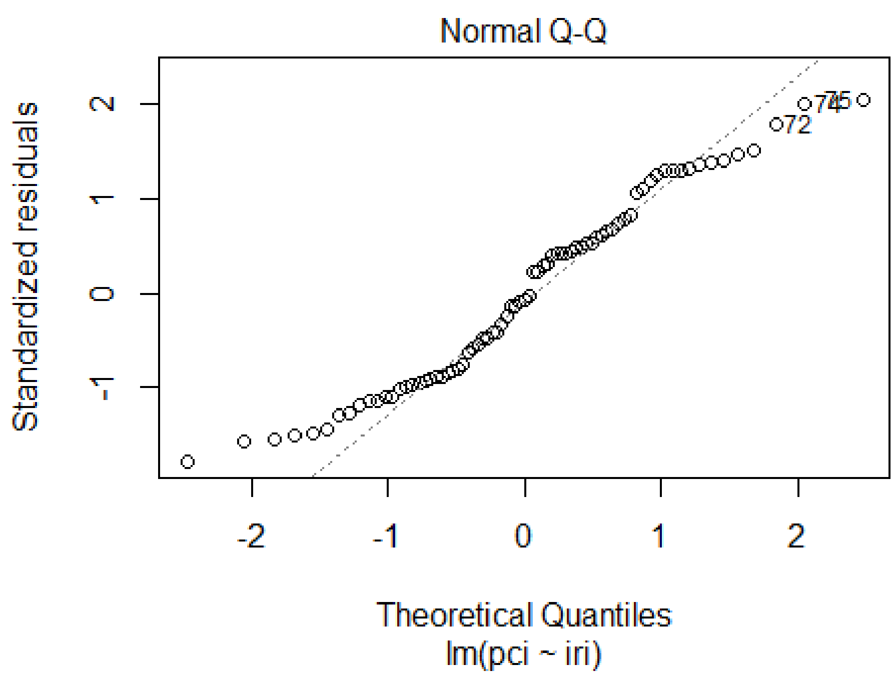
7.3.2 Models

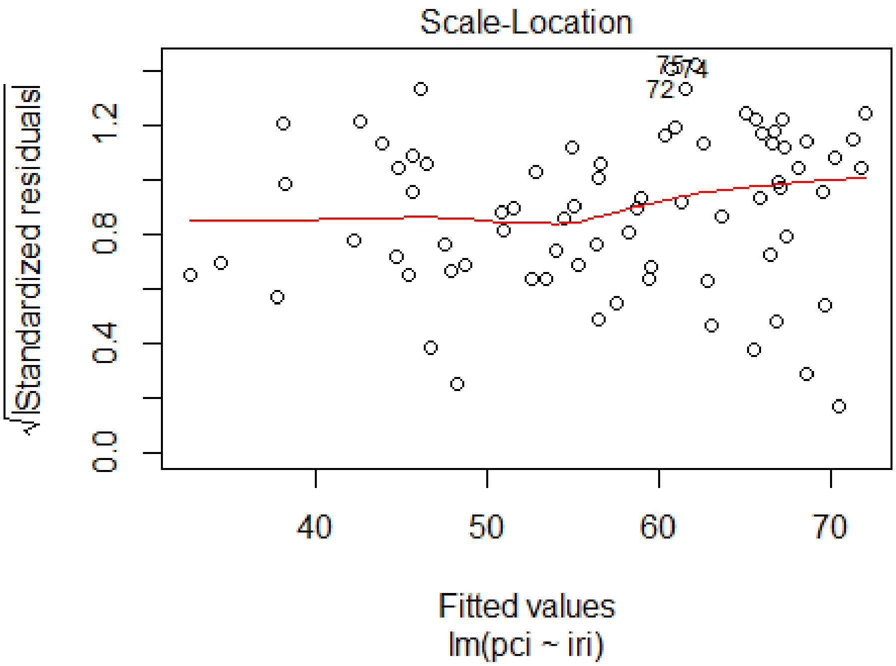
We try first a linear model, then a nearest neighbour model, and then a random forest model to analyse possible machine learning approaches.

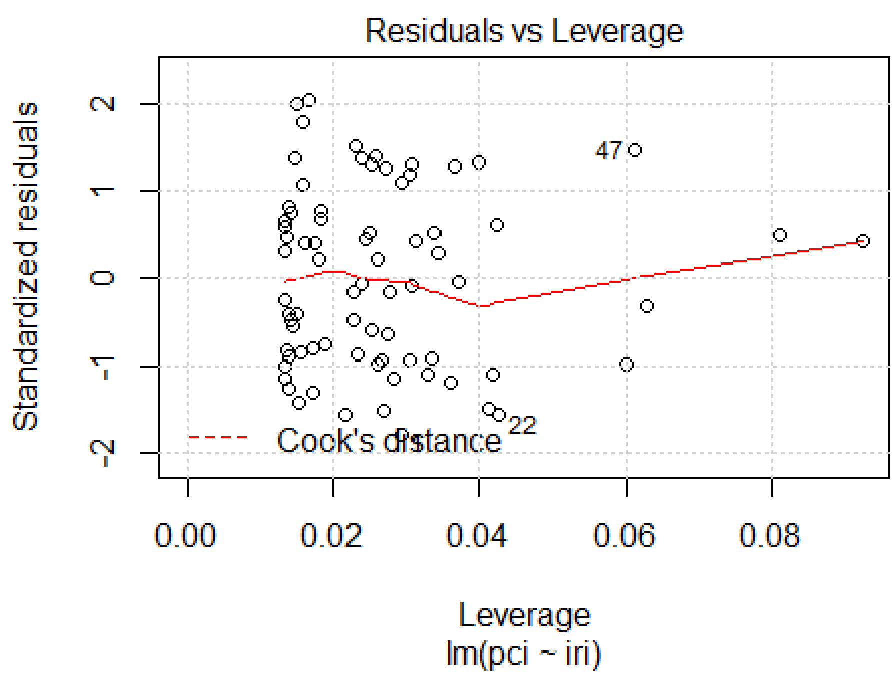
7.3.2.1 Linear Model

```
fit_lm=lm(pci~iri, data = data)

summary(fit_lm)

##
## Call:
## lm(formula = pci ~ iri, data = data)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -32.074 -16.218  -1.163  12.847  36.949
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   90.558      7.364  12.297  < 2e-16 ***
## iri          -10.442      2.199  -4.748 9.98e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 18.32 on 73 degrees of freedom
## Multiple R-squared:  0.236,  Adjusted R-squared:  0.2255
## F-statistic: 22.54 on 1 and 73 DF,  p-value: 9.979e-06

plot(fit_lm)
```


Residuals vs Fitted
Residuals
40
20
0
-20
-40
75
74
72
40
50
60
70
Fitted values
lm(pci ~ iri)

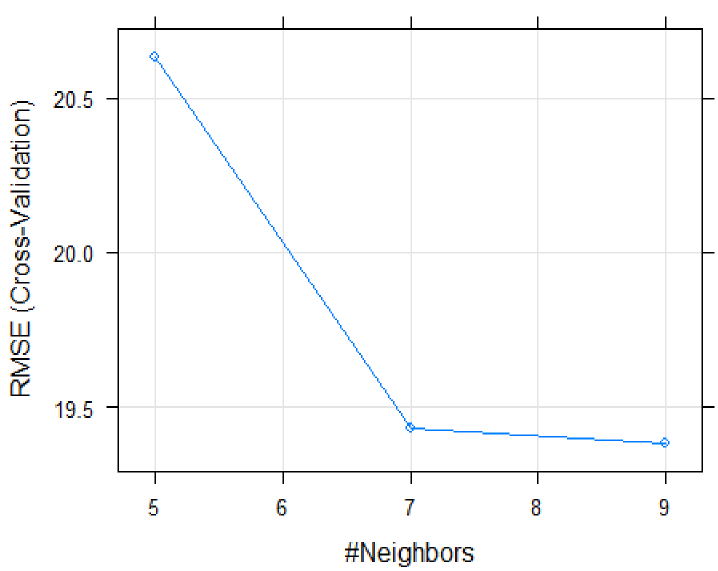

Normal Q-Q
Standardized residuals
2
1
0
-1
74
75
72
-2
-1
0
1
2
Theoretical Quantiles
lm(pci ~ iri)


Scale-Location
√|Standardized residuals|
0.0
0.4
0.8
1.2
40
50
60
70
Fitted values
lm(pci ~ iri)
75
74
72


Residuals vs Leverage
Standardized residuals
-2
-1
0
1
2
0.00
0.02
0.04
0.06
0.08
Leverage
lm(pci ~ iri)
47
22
Cook's distance

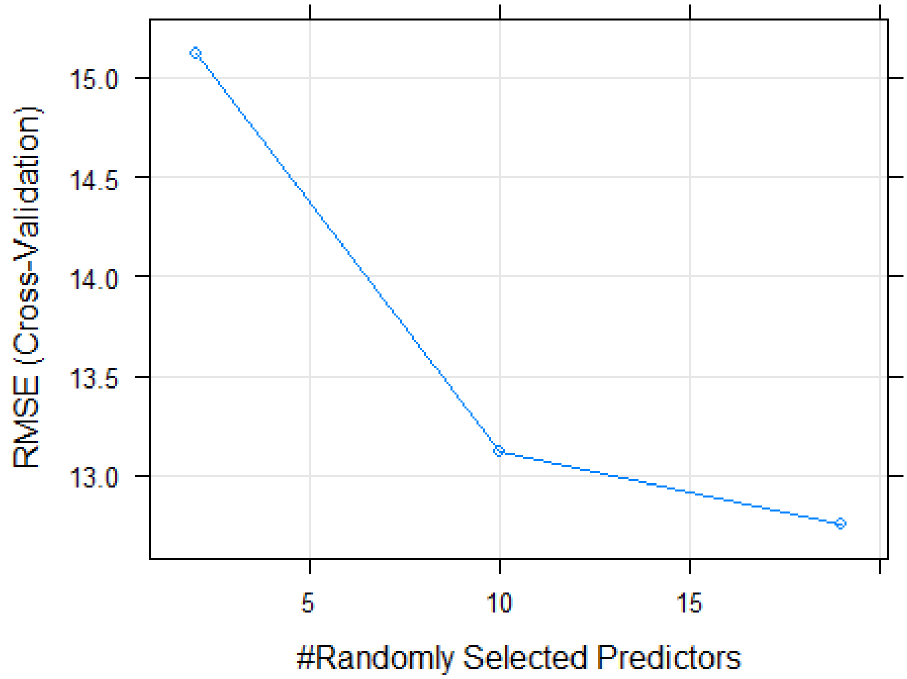
7.3.2.2 Nearest Neighbors

```
fit_knn = train(
  pci ~ iri,
  data = data,
  method = "knn",
  trControl = trainControl(method='cv',number = 5)
  )

fit_knn

## k-Nearest Neighbors
##
## 75 samples
##  1 predictor
##
## No pre-processing
## Resampling: Cross-Validated (5 fold)
## Summary of sample sizes: 60, 60, 59, 60, 61
## Resampling results across tuning parameters:
##
##   k  RMSE      Rsquared   MAE
##   5  20.63490  0.1610891  17.76946
##   7  19.42948  0.2047556  17.09264
##   9  19.38052  0.1936146  17.05062
##
## RMSE was used to select the optimal model using the smallest value.
## The final value used for the model was k = 9.

fit_knn$results

##   k     RMSE  Rsquared      MAE  RMSESD RsquaredSD    MAESD
## 1 5 20.63490 0.1610891 17.76946 2.19431  0.1222830 2.416988
## 2 7 19.42948 0.2047556 17.09264 1.57143  0.1528751 1.779502
## 3 9 19.38052 0.1936146 17.05062 1.68053  0.1266733 1.707211

plot(fit_knn)
```



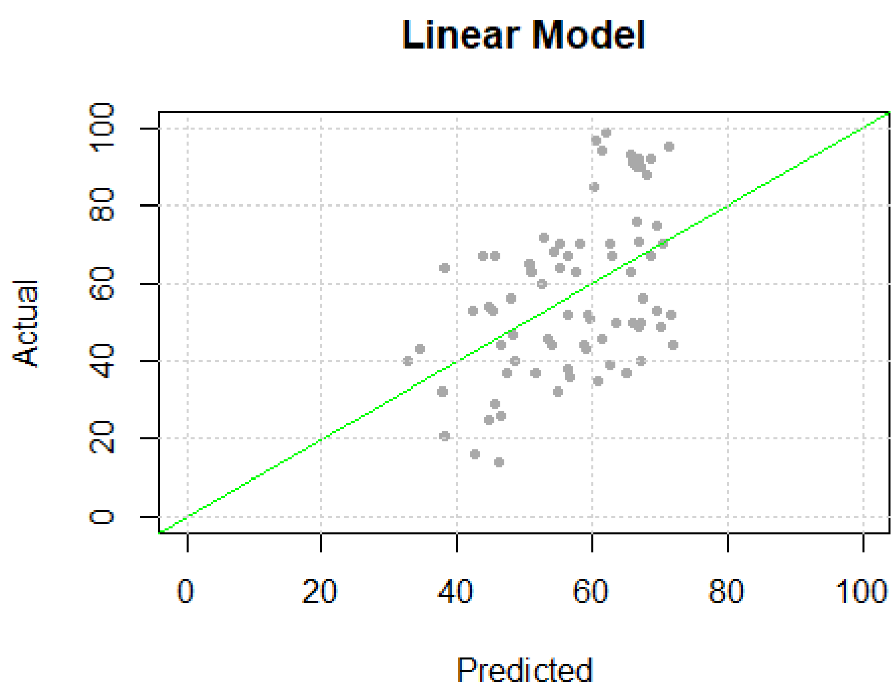
7.3.2.3 Random Forest

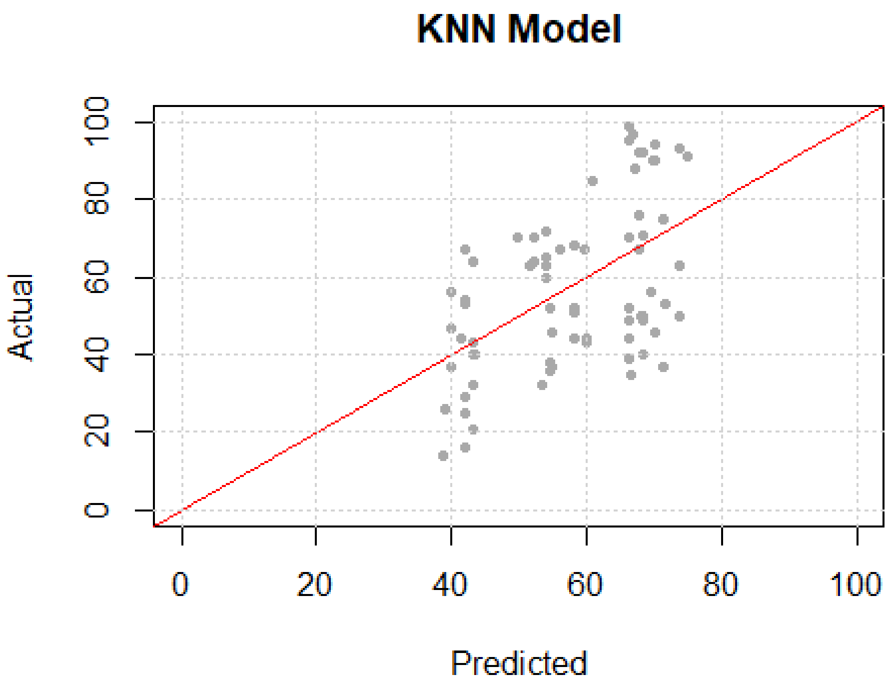
```
fit_rf = train(
  pci ~ iri+st,
  data = data,
  method = "rf",
  trControl = trainControl(method='cv',number = 5)
  )

fit_rf

## Random Forest
##
## 75 samples
##  2 predictor
##
## No pre-processing
## Resampling: Cross-Validated (5 fold)
## Summary of sample sizes: 59, 60, 61, 60, 60
## Resampling results across tuning parameters:
##
##   mtry  RMSE      Rsquared   MAE
##    2    15.12385  0.6035703  12.84597
##   10    13.11961  0.6075963  10.51618
##   19    12.75191  0.6296628  10.07108
##
## RMSE was used to select the optimal model using the smallest value.
## The final value used for the model was mtry = 19.

fit_rf$results

##   mtry     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1    2 15.12385 0.6035703 12.84597 2.092102 0.06572844 1.222715
## 2   10 13.11961 0.6075963 10.51618 1.785553 0.04762010 1.180347
## 3   19 12.75191 0.6296628 10.07108 1.644128 0.05001152 1.100144

fit_rf$finalModel

##
## Call:
##  randomForest(x = x, y = y, mtry = param$mtry)
##                Type of random forest: regression
##                      Number of trees: 500
## No. of variables tried at each split: 19
##
##           Mean of squared residuals: 199.0633
##                     % Var explained: 53.43

plot(fit_rf)
```

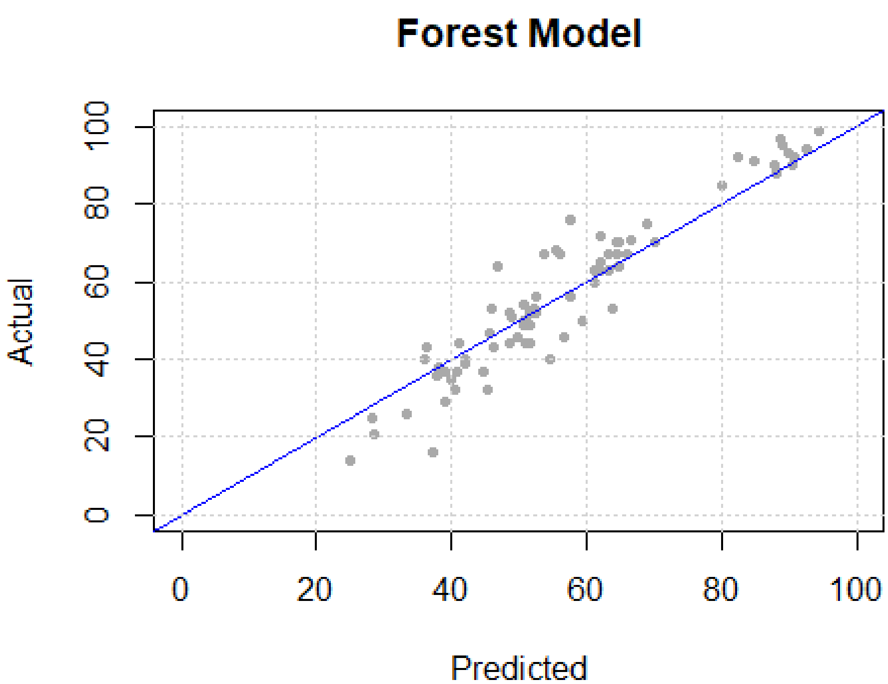


7.3.3 Predicted vs. Observed Values

The predicting quality of each model is shown below contrasting the observed and predicted values.




KNN Model
Actual
Predicted
0
20
40
60
80
100


Forest Model
Actual
Predicted
0
20
40
60
80
100