Can the method for calculating the International Roughness Index used by the company Infrafocus be certified according to Dutch regulations?

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ABSTRACT

The International Roughness Index (IRI) was developed in the 1980s in the United States of America as a way to estimate the longitudinal road roughness in order to be able to evaluate and maintain road infrastructure in an easy and standardized way. It can be determined by driving with a prepared vehicle, often referred to as High Speed Road Profilers (HSRP), over the road, and measuring the difference in suspension in the wheels by using different sensors over time. Nowadays, it is internationally recognized as a valid measurement, both in America and also in Europe, and also the methods for measuring the necessary data and calculating the index from this data are internationally standardized, e.g. how precise and accurate the sensors must be. The company Infrafocus is using a software called *Road Doctor* from a Finnish company called *Roadscanners* which provides two methods that both use Inertial Measurement Unit (IMU) data to derive the road profile, instead of measuring it directly with conventional sensors such as a walking stick or a laser. Since it is not exactly fulfilling the requirements of the certified IRI measurement, this method is not applicable in field work. The purpose of this research will be to compare these methods and their results to find out whether the technique used by Infrafocus is still applicable to calculate the IRI.

Keywords

International Roughness Index, Road Maintenance, Infrastructure, Infrafocus, Roadscanners, Road Doctor, High Speed Road Profiler

1. SCOPE

1.1 Detailed description of this project

The effort of this research project is mostly dedicated towards comparing the methods for calculating the International Roughness Index, and determining whether they give the same values for the same underlying data. Namely, the two methods used by Infrafocus (i.e. the ones that *Roadscanners* implemented), will be compared to the official specification. As previously mentioned, one goal of this research project is to determine whether these methods can be applied in the Netherlands, therefore it also needs to be investigated what criteria there are and whether these two methods meet this criteria. This is why this needs to be investigated first before the comparison can be made, so that a proper decision can be made whether or not these methods fulfill the regulations.

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1.2 Research questions

In order to assess the success of this research, the purpose of this research needs to be well defined, as well as the questions that need to be answered with this research. Hence, these questions are given below:

- How exactly is the software from *Roadscanners* calculating the IRI? What data does it use, and is it using the *Golden car* model with the fixed parameters? If not, what mechanical model is it using, with what parameters? Does the method differ from the official specification, and if so, how?
- What exactly are the criteria given by the Dutch authorities to get such a method certified? How much can the value measured by Infrafocus deviate from the true IRI value that has been measured with a certified method? What does the administrative procedure for certifying measurement methods in the Netherlands with regards to road infrastructure look like?
- Does the method from Infrafocus, namely using the software *Road doctor*, fulfill the requirements from the Dutch authorities so that it can be used in field work?

If all these questions can be answered with this research, it can be considered successful and insightful.

2. APPROACH

First, the historical context of the International Roughness Index will be investigated to provide some background. Then, the official specification will be discussed in detail. It will be investigated what sensors are applicable in field work, and how the mechanical modelling in general can be done. Besides that, it will be demonstrated how this value can be interpreted and understood, and how it can be related to the type of the road together with the typical travelling speed. After the IRI has been explained in full detail, the related work will be discussed and evaluated. Followed by that the regulations concerning the IRI and

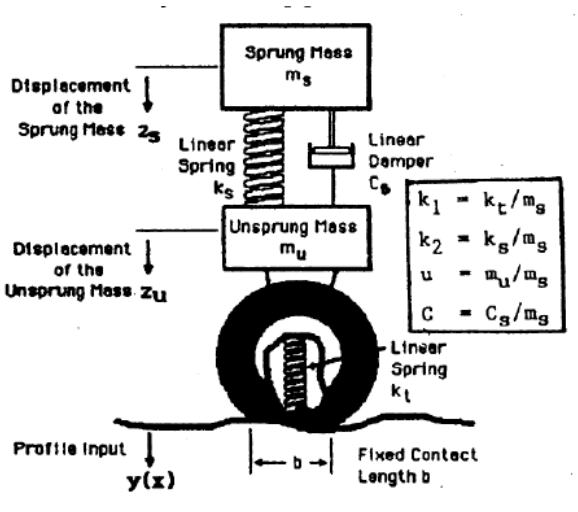

Figure 1. Golden car (or quarter car) model (Coremans 2007)

HSRP are demonstrated. Then, the methods which are used by *Roadscanners* will be explained in detail, accompanied by possible problems with this method. When the whole context is given and explained in detail, the actual experiments will be explained. The setup and tooling will be described, as well as the goals of the experiments, the difficulties and the expected outcome. Finally, the results will be presented and discussed. In the end, a conclusion will be drawn and a recommendation to Infrafocus will be made.

3. HISTORY AND ORIGINAL SPECIFICATION OF THE IRI

3.1 History

In the early 1980s, it was observed in the United States of America that measuring the roughness of roads was essential to determine their quality. At the same time, it was observed that this measurement process differed from agency to agency, due to different equipment and techniques being used. This caused the measurements to not be reproducible, sometimes even within the same agency. Hence, measurements were incorrect and not reliable, and thus, a standardized way of measuring needed to be found (T. D. Gillespie, M. W. Sayers, and Segel 1980). In 1982, a collaborative effort was pushed forward to investigate and perform research on the matter by multiple institutions all across the world from countries such as the US, Brazil, Belgium, the United Kingdom, and France. Among these institutions were road maintenance agencies and departments, research institutes, but also the World Bank. This led to the International Road Roughness Experiment in 1982 which was conducted in Brazil, and led to the first official definition of the International Roughness Index (T. D. Gillespie, M. W. Sayers, and Segel 1986). Since then, the definition of standards and guidelines for this index has been completely overtaken by the World Bank.

3.2 Official specification

According to the official guideline that describes the International Roughness Index, it is defined "as a characteristic of the longitudinal profile of a travelled wheeltrack, rather than as a characteristic of a piece of hardware, in order to ensure time stability. Thus, direct measurement of the IRI requires that the profile of the wheeltrack be obtained."(Michael W. Sayers, Thomas D. Gillespie, and Paterson 1986). This ensures that the hardware used for the measurement cannot influence the calculation, and therefore ensures the robustness of such a measurement. Most commonly this two-dimensional, longitudinal road profile is measured using a laser near one of the rear wheels which measures the distance to the ground periodically. More details about the requirements of the sensors and the types of sensors that are allowed can be found in section 3.4.

These discrete sample points are then filtered and extrapolated in order to produce a continuous function which is actually usable in the calculation. The next step is to calculate the forces that are applied to a standard vehicle when driving across the measured road profile at 80 km/h. This simulation is using a mechanical model called "Quarter car model", which models the suspension and damping of one wheel (hence, Quarter Car since only one quarter of the car is modelled). This model can be seen in figure 1. The parameters for this model are defined in the IRI specification in relation to the sprung mass m_s, and are as follows:

$$c = c_s/m_s = 6.0$$

$$k1 = k_t/m_s = 653$$

$$k2 = k_s/m_s = 63.3$$

$$\mu = m_u/m_s = 0.15$$

Here, k_s stands for the spring constant between the two masses (vehicle mass m_s and tire mass m_u), and k_t for the one from the tire, while c_s is the damper of the sprung mass. The damping effect of the tire is neglected in most models, since it is infinitesimal and therefore, does not have any significant effect on the simulation. The quarter car model is described by differential equations shown in formula 1 and 2.

$$m_s * z_s'' + c_s(z_s' - z_u') + k_s(z_s - z_u) = 0 \quad (1)$$

$$m_u * z_u'' + c_s(z_u' - z_s') + k_s(z_u - z_s) + k_t(z_u - z_r) = 0 \quad (2)$$

All these symbols and variables correspond to the ones previously explained, z_r here means the road profile. Often these equations are represented as matrices, as this allows for an easier calculation, and also an easier transformation into code. For completeness, these are shown in formula 3.

$$x' = A * x + B * z_r \quad (3)$$

x' is the matrix representing the state variables, z_r is again the filtered road profile. The definitions for x, A, and B are shown in equations 4, 5, and 6 respectively.

$$x = \begin{bmatrix} z_s \\ z_s' \\ z_u \\ z_u' \end{bmatrix} \quad (4)$$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_2 & -c & k_2 & c \\ 0 & 0 & 1 & 0 \\ k_2/\mu & c/\mu & -(k_1 + k_2)/\mu & -c/\mu \end{bmatrix} \quad (5)$$

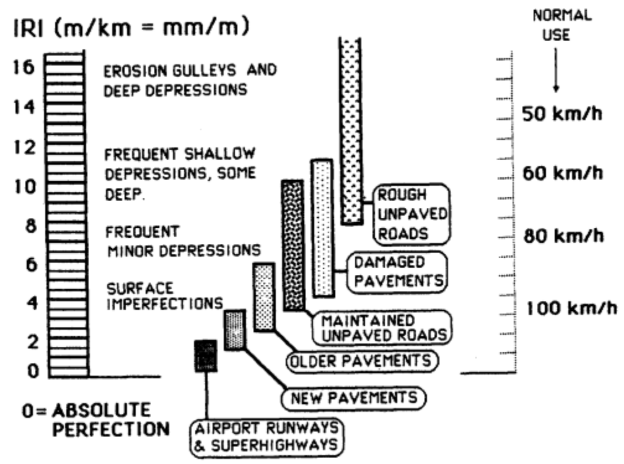

Figure 2. The IRI roughness scale (Michael W. Sayers, Thomas D. Gillespie, and Paterson 1986)

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ k_1/\mu \end{bmatrix} \quad (6)$$

In this research, the mechanical modelling was conducted in a different manner which is why these matrices will not be mentioned anymore. How the experiments were conducted and how they differ from the matrix method is explained in section 7.

The differences in speed of displacement of the two masses are then aggregated and divided by the length of the road that is being investigated. The formula for that can be seen in formula 7.

$$IRI = \frac{1}{b}\int_0^T |z_s' - z_u'|dt \quad (7)$$

Since z_s and z_u stands for the the displacement of the sprung mass (the vehicle) and the unsprung mass (the tire) respectively, z_s' and z_u' stands for the first derivative of these displacements, i.e. the velocity towards and from the ground. T stands for the time, while b stands for the profile length that is also shown in figure 1. This profile length serves to normalize the IRI, and is typically around 250 to 300 mm.

3.3 Interpretation of the IRI

The International Roughness Index is given in m/km which can already be seen from the formula as the differences in velocities are integrated (which gives a distance/displacement), and then divided by the length of the examined road. Generally, a lower IRI is desirable as it implies less vertical force applied to the vehicle. The lowest value for the IRI is 0 m/km, while the upper bound is theoretically unlimited. In practice however, a value of 15 m/km is already extreme and resembles that of a completely broken road. The World Bank has, together with the guidelines on how to calculate the IRI, included a graph which demonstrates how roads and the usual driving speed correlate with the IRI. This overview can be seen in figure 2. It is also important to mention that the IRI is computed for sections of the road that have an equal length. Typically, these sections are 10, 20, 50 or 100 m long. This heavily depends on the type and precision of the used sensors.

3.4 Sensors

In order to correctly measure the road profile with proper accuracy and precision, the sensors used in the measurement must follow guidelines and standards defined both by the American Society for Testing and Materials (ASTM), and of course the World Bank. According to the ASTM, the distance between samples in the measured road profile must not be greater than 25 mm, and the precision must be smaller than 0.38 mm. All sensors must be able to follow these standards, otherwise the measurement cannot be accepted. The World Bank also defines several classes with regards to the sensors. Class 1 represents the highest accuracy and includes laser profilers such as "noncontact lightweight profiling devices and portable laser profilers", but also manually operated devices such as Dipsticks and walking profilers (Múčka 1995)[1]. Class 3 is of lower quality, and includes correlational measurements, e.g. accelerometers, while Class 1 is independent of speed. Additional sensors that might be used, but yield lower accuracy, include ultrasound, bump integrators, and even cell phones using apps. All of these can be considered Class 3, except for the apps which are Class 4. Due to the higher accuracy and precision, Class 1 can determine the IRI of sections as short as 10 or 20 m, while Class 3 typically only gives accurate values for sections of length 100 m. In World Bank terminology, these classes are often referred to as Information Quality Levels (IQL)(Bennett, Solminihac, and Chamorro 2006).

4. RELATED WORK

Peter Múčka has published an overview about IRI specifications all around the world (Múčka 1995). In his article, he describes standards and practices in 35 US states and 29 non-US states, together with the IRI thresholds for certain road types and their corresponding, typical driving speeds. These thresholds are not important for this research, as it focusses more on the methods used for measuring and calculating the IRI, and not so much how high this value is allowed to be.

Another topic that received quite some attention is predicting the progression of the IRI in the future using Neural Networks and other Machine Learning techniques. An example of that is one study published in the International Journal of Pavement Engineering that was written by members of the Faculty of Engineering Technology of the University of Twente (Ziari et al. 2015). Here, the researchers tried different types of Neural Networks to estimate how the IRI changes within the next three years, and compared them against each other. Although this topic is interesting, it is not relevant to this research as the study was not concerned with different measuring techniques.

Most, if not all, the research that concerns the methods and techniques itself, were conducted by the World Bank itself, because it is the organization that formulated the official specification. Among these studies, the Technical Papers 45 (see reference T. D. Gillespie, M. W. Sayers, and Segel 1986) and 46 (see Michael W. Sayers, Thomas D. Gillespie, and Paterson 1986) are most important, since this is the official specification, and a set of guidelines on how to calibrate sensors, measure the road profile, and perform the simulation and calculation. Therefore, at least

[1]Dipsticks and walking profilers were mostly used in the 1980s. Nowadays, there are not used anymore due to the advancement and the improved usability of laser profilers.

for the technical part, this research will mostly discuss these papers.

5. DUTCH REGULATIONS AND CROW

There is no specific law or regulation regarding the IRI itself, nor about how precise or accurate measurements must be. Also, there are no legally binding restrictions on newly constructed roads or maintained roads with regards to their IRI value. However, all these things are regulated by the so-called Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek (CROW). This organization was founded in 1987 when multiple foundations merged, and over the years other organizations were merged into CROW as well. They describes themselves as a knowledge platform (see CROW 2021), and conduct research on all kinds of infrastructure and the construction and maintenance thereof, and construction in general. This foundation publishes their findings, guidelines and standards, and offers courses to teach companies, cities, and municipalities on how to implement and follow these. Also, they offer certifications if these guidelines are followed correctly. These guidelines however are not legally binding, they only serve as advice. Due to the high reputation in the Netherlands and vast amounts of knowledge due to the amount of experts involved in this foundation, these certificates are in most cases expected from companies by cities and municipalities. Therefore, it is highly advised and recommended to follow these standards and practices.

5.1 Sensor requirements

In a report from May 2019, CROW explained the necessary requirements to get an HSRP certified (see CROW 2019). The guidelines for the sensors follow the ones defined by ASTM. According to CROW, sensors must be of Class 1 in order to be able to produce accurate enough values. Additionally, laser scans must fulfill at least these additional requirements:

- Measurement resolution: 2.5 to 50 mm
- Vertical measurement length: at least 60 mm
- Horizontal measurement length: at least 200 mm
- Vertical resolution: at most 0.05 mm
- Vertical non-linearity: at most 2% of the entire measurement range
- Measurement interval (or distance between samples): at most 1 mm
- Background noise expressed in RMS: at most 0.05 mm

Besides that, CROW defines two major demands: accuracy and precision. They define accuracy as the closeness between the measured and the true value, and precision as reproducibility. This means, according to their definition, that for measurements conducted shortly after another, the result should always lie in the 95% confidence interval, meaning +/- 2.82 times the standard deviation.

5.2 Admission procedure

The document (CROW 2019) also describes an admission procedure, where a HSRP is tested against all the aforementioned requirements. If the vehicle fulfills the requirements, it will receive a certificate so that it can be used in field work. First, all the sensors are checked. This part of the procedure is not relevant for this research, so it will not be explained. For more details on this, refer to the document. The second part is actual field work, where the vehicles will drive across a track while measuring the road profile. This test track must be at least 150 m long, and can be either a regular road, an airfield strip, or some other kind of asphalt. It can be augmented by speed bumps or railway crossing signs to virtually increase road roughness. Besides that, the measurement speed must be at least 25 km/h. Then, the IRI will be calculated from that data and compared to a reference. This reference can either be an already existing road profile that was shown to be precise, or the average of other vehicles that take part in this procedure at the same time (if there are any). In addition to the road profile and the IRI, the HSRP operator must be able to answer multiple questions, such as the difference between the highest and lowest elevation point or the average elevation of a particular point. Every vehicle must complete this measurement ten times, while fulfilling the reproducibility criteria as described earlier. When this procedure is successfully completed, the certification is given for the HSRP.

5.3 Evaluation of this procedure

Since there is no real ground truth in this procedure and all measurements are simply compared to other participants of this procedure, there might be a case where all participants calculate the same (or at least reasonably close) wrong value, and are therefore all certified because the difference to the reference was small enough. Of course, this scenario is highly unlikely due to all the precautions, and assuming that most of these vehicles will produce a value that is close to the unknown ground truth. Besides that, this ground truth cannot be known because this created a "chicken or the egg" dilemma that cannot be solved, because in order to verify a measurement, it must be compared to a reference that must have been verified before, and so forth. Therefore, this kind of evaluation is most likely the closest approximation to the true IRI value.

One issue with regards to this research project in particular is that the research question is much harder to answer now since the methods for calculating the IRI are not really important as long as they produce a value that is close to the given reference. Hence, comparing a measurement technique to the official specification might be useful, however, it does not guarantee that this technique will be certified. The implications of this will be discussed later when the actual experiment will be explained. Before that discussion, the method of *Roadscanners* is explained and how it differs from the official specification.

6. ROADSCANNERS METHODS

In this section, the method that the company Roadscanners implemented for the IRI calculation in their *Road Doctor* software, and which Infrafocus is using, is discussed. The main difference to the official specification is that the road profile is not measured with laser scans, but rather calculated. Instead it is using the data coming from an Inertial Measurement Unit to measure the forces that are applied to the measurement vehicles, derive the road profile from that data, and then perform the mechanical modelling described in the official specification. The advantage that this method has is that it is relatively cheap to implement since IMUs are generally much less expensive than laser scanners, and assuming the IMU is correctly calibrated, it produces reasonably precise and accurate measurements. On the other side however, there are some issues with IMUs in general since they tend to have small inaccuracies which over time accumulate. This causes the value to shift exponentially from the correct value if not calibrated correctly with GPS data (see Siciliano and Khatib 2008).

Strictly speaking, there are two methods that *Road Doctor* is using. The first method is using the acceleration of the Z-axis (up and down movement) together with the timer value to calculate the vertical displacement of the vehicle, i.e. the road profile, by integrating the acceleration twice using the time that has passed. The other method is using the Pitch measurement, so by what angle the vehicle is tilted towards the ground, and the distance that the vehicle already travelled. From these discrete points and some filtering, a continuous function can be derived which resembles the road profile. Both methods will then use the road profile to perform the simulation and modelling described in the official guidelines and calculate the IRI according to these methods. This is what is described in the *Road Doctor* manual (Roadscanners 2019).

Detailed information about the Pitch and the Acceleration method are not available unfortunately, because neither Infrafocus nor *Roadscanners* provided that information. Thus it is unknown how the mechanical modelling is exactly conducted, and how the data is processed and filtered.

7. EXPERIMENTAL SETUP

7.1 Goals of these experiments

Multiple experiments will be conducted. First, the laser scan data will be transformed into a road profile which will be considered the ground truth from now on. In section 7.3, the underlying data is further explained, including where this data is coming from. Then, this road profile will be compared to what the two *Roadscanners* method produce. By that, it should be tested whether the techniques that use IMU data for calculating the road profile actually produce the correct profile, i.e. the ground truth that is the laser scan. Also, the outcome of the simulations will be compared. This is simply to verify that the modelling also gives the same result.

7.2 Tools

For handling the data, Python will be used as it provides an easy way of processing text files. Together with the library Numpy, which is often used in the scientific domain, it provides a powerful tool set to handle large amounts of data, and allows for fast calculations. It also helps with converting data into a format that 20-sim understands. This tool can be used for modelling all kinds of mechanical, electrical, and even fluid systems. It is similar to Simulink, a library for Matlab, and will be used to model the suspension of a car by implementing the Quarter Car Model.

7.3 About the data sets and processing them

The data is provided by the client Infrafocus. One could argue that this could potentially lead to a conflict of interest since they might have influenced or altered the data in such a way that the experiments will give exactly the same values, meaning that their method would be according to the official specification. However, this would result in them not benefiting from this research project, as they would not gain any knowledge. Also, this research project alone will not guarantee them that their method will be certified, since a positive result in this paper will not allow them to skip the CROW procedure in any way. Therefore, it would be in Infrafocus' best interest to provide the raw, unaltered data.

The data is from two different public roads, and were both measured in an actual field work project in the province of Drenthe. It contains both the raw measurements and the measurements that were filtered by *Road Doctor*. It also includes the calculated road profile for each of the two methods, together with the IRI value resulting from that road profile. The IRI values are given in the interval of 10 m which is why the model of this research also computes the IRI values for this interval.

Both measurements include these data sets, which are the filtered outputs from *Road Doctor*:

- AccIRI1_ROAD1_SEC1__<*timestamp*>.txt:
  –> Road profiles and IRI values based on IMU data
- LsAng1_ROAD1_SEC1__<*timestamp*>.txt:
  –> Laser scans of the rotating laser at the rear of the vehicle

Other files that were not mentioned are the raw data sets, meaning the raw sensor values, and also other non-relevant data sets such as PASHR_ROAD1_SEC1__<*timestamp*>.txt which is simply the IMU data in another data format. These text files are similar to Comma Separated Values (CSV) files, the difference being that the values are not separated by a comma but by a tabulator. Similar to CSV files, the data is formatted as a table, where the first line represents the name of the columns. In order to parse and process this data, Python was used. The function for parsing the TXT file can be seen in appendix A. The AccIRI file shows the output of *Road Doctor* and includes, as already mentioned, the calculated road profile and the IRI values. For both methods described in section 6, there are two columns: one for the computed road profile, namely Acc_Prof and Pitch_Prof, and one for the calculated IRI value, namely Acc_IRI and Pitch_IRI. Additionally, it contains columns for indicating which section of the road is examined by including the start and end position of this section[2]. These columns are named "From" and "To".

The LsAng file that contains the laser scans is by far the largest file with about 238 MB for the first measurement, and 335 MB for the second. The first row in this file contains information about the configuration of the

According to Roadscanners 2019, columns named "A_<degree>" consist of distances from the scanner to the object at rotation <degree>, while columns named "R_<degree>" indicates the reflectivity/remission value of the object. The latter is not important for this research, and therefore ignored in this research. The manual also mentions another column named "Z_<degree>" which is not present in the data set, and therefore only mentioned here for completeness. The value at 90° resembles the measurement of the point perpendicular to the ground, and was therefore used to calculate the road profile. Another attempt was to simply select the minimum distance, however, that proved to be quite unstable as sometimes values on the side of the vehicle were selected. This might have been caused by tall vehicles or walls next to the measurement vehicle, but this is just an assumption. Another issue was that the measurements were not exactly 90°, which is why for each row the closest degree to 90 was chosen. Both helper functions can be seen in appendix C, together with the function that actually calculates the road profile from these distances.

[2] "Position" meaning the offset in m from the starting point.

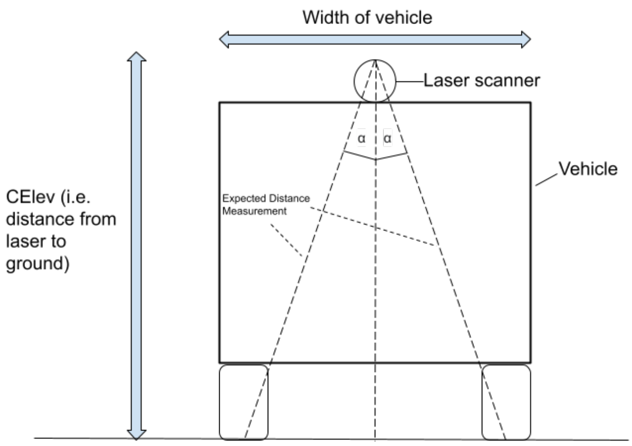

Figure 3. Calculating road profiles based on laser measurements for different angles/wheel paths.

This is achieved by taking the CElev value from the first row, as it indicates the height at which the sensor is attached (in other words, the distance from the sensor to the ground, when the vehicle is standing on an even surface), and subtract the measured distance to the ground. This calculation would result in the road profile in between the two wheel paths since the laser is attached in the middle of the vehicle. Since the IRI is normally computed based on the wheel paths and not in between them, two more road profiles were computed using basic trigonometry. A visualization of that can be seen in figure 3. Based on the height of the sensor and the width of the vehicle (160 cm), the measurement angle was calculated by equation 8 which gave 14.61°. Also, the estimated measurement was calculated with formula 9.

$$\alpha = tan^{-}1((Width/2)/CElev) \approx 14.61 \deg \quad (8)$$

$$Estimateddistance = \sqrt{CElev^2 + (\frac{Width}{2})^2} \quad (9)$$

Now, the road profile for the left and the right wheel path was obtained by subtracting the actual distance at 75.39° (or rather the closest to that degree) for the left, and 104.61° for the right wheel path[3], from the expected distance. The implementation in Python can be seen in appendix C.

Another thing that needed to be done for both data sets is to add a timer to accurately simulate driving at 80 km/h, since 20-sim needs timing for the simulation. This was achieved by calculating the travelled distance and calculating what that corresponds to in milliseconds. For the LsAng file, this is done by differentiating the total travelled distance given in the data set, and for the AccIRI file, the difference could be calculated by subtracting the "To" column from the "From" column. The implementation for LsAng can be found in appendix C, and the one for AccIRI can be found in appendix D.

7.4 20-sim

As previously mentioned, simulating the behaviour of the car suspension with the Quarter Car Model with the Golden Car parameters was done with 20-sim. Here, the mechanical equations 1 and 2 mentioned in section 3.2 were directly translated into a block diagram which can be seen in appendix E. The parameters of the car are those of the Golden car model by calculating the different mechanical parameters based off a constant mass of 500 kg. This was necessary because the Golden car parameters are normalized based on the weight, and the mechanical model on the hand needs the exact values for the parameters, not simply the relations between them. This model takes the road profiles mentioned in section 7.3 as an input by reading the processed and altered files, and returns both Z'_u and Z'_s, and also the difference of these two.

This is then fed into the next model, namely the IRI calculation, which can be seen in appendix F. This model first computes the absolute difference between Z'_s and Z'_u, and then integrates the signal in the last 0.45 s since this is the time it takes to travel 10 m at 80 km/h. Since Z'_s and Z'_u are given in m/s and the IRI is given in m/km, it needs to be converted by multiplying by 45. This conversion is also explained in Sawyers 1995. After this conversion, the IRI is divided by 250 mm for the profile length (or rather multiplied by 4, as the IRI is given in m). This is an exact implementation of the formula shown in section 3.2. These two submodels (the Golden Car model and the IRI calculation) are used in the complete model which imports the road profile data produced by *Road Doctor* and the Python scripts, computes a moving average to remove large outliers using integration over a timespan of 0.1 s and dividing by 0.1 s, and computes the IRI values for these profiles.

7.5 Expected result

It can be expected that the results a similar, if not exactly the same. The IMU used by Infrafocus is highly accurate and produces measurements at a sufficient frequency, therefore it will most likely result in IRI values that are sufficiently close to the ground truth, i.e. the laser scans. Since the Acc_IRI method is already described as being inaccurate by *Roadscanners* itself, it can be expected that this method will produce values that strongly deviate from the truth. The Pitch_IRI method however seems promising, and will most likely produce the correct road profile. It is not entirely clear what effect the difference in the different wheel paths might have, as it might change the entire outcome of the experiment if there is a bump on one of the wheel paths, but not on the other two. These deviations might have an impact on this research, and thus, the differences need to be compared. However, due to the length of the examined road these differences will most likely even out.

Another thing that might cause problems with the experiment is that the calculations from *Roadscanners* for the road profiles, namely Acc_Prof and Pitch_Prof, do not have a high resolution since they only show the profile for the examined section which is 10 m. This could potentially cause issues when verifying the mechanical modelling. Also, it is not entirely clear whether this data is simply an average or an integrated accumulation.

One additional aspect about sensors in general is their calibration. In order to be certain that the measurements are correct, all the sensors either do not need calibration due to their nature (such as the 360° laser scanner that provides the LsAng profile), or are calibrated beforehand (e.g. a radar scanner which scans the ground up to 2 m deep). Some sensors even calibrate themselves (such as the XSens IMU which is used by Infrafocus). Therefore,

[3]Actually, it is not entirely clear from the measurements which side is left or right. For this research however, this is not important.

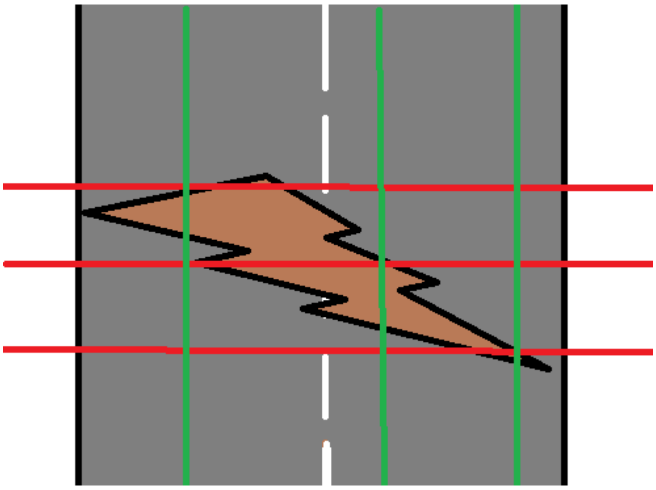

Figure 4. Why taking the average would be bad: The brown area resembles a road bump, the red lines resemble measurement points, and the green lines resemble the left, middle and right wheel path. The road bump would appear much longer and not as severe in the average road profile.

it is not very likely that calibration issues did affect the measurement.

7.6 Methodology

Since it cannot be exactly determined whether the *Roadscanners* method can be certified, it will be investigated whether it produces the same results as the official specification. The 95 % confidence interval used in the CROW procedure will also be used in this research to allow for a small margin of error. As ground truth, both the left and the right profile obtained by the LsAng data was used. This is because it resembles the closest measurement to the actual specification since the road profile is measured for the actual wheel path, and not in between those paths. Another reason against using the middle road profile is also that it might be much smoother since the wheels rarely touch this section of the road, and therefore, the road is significantly less damaged. Another possibility would be to simply compute the average of the road profiles and take that as ground truth, but this might severely deviate from the actual truth. An example of this can be found in figure 4, where for the separate road profiles one road bump only appears in one measurement point for each wheel path, and also only in one wheel path at the same time. When taking the average wheel path, the road bump will appear much longer in the road profile and also much less severe due to averaging the road bump with two other road profiles that are smooth.

In order to verify the mechanical modelling, the IRI will also be calculated from Acc_Prof and Pitch_Prof, and compared to Acc_IRI and Pitch_IRI respectively. In the following sections, the road profiles itself will be shown and compared, together with the computed IRI values. Then, the IRI values will be discussed and a final recommendation will be made.

8. RESULTS

In appendix G, the different road profiles are shown for the different wheel paths. In both data sets, it can be seen that these road profiles are almost the same, both the positions of of peaks and the amplitudes of these peaks overlap. There are some differences, these are very minor however. One thing that needs to be mentioned is the offset that can be observed when comparing the graphs to each other. That offset will have a slight impact in the beginning of the mechanical modelling, since the initial value is set to 0 and will increase more (or less) rapidly with a higher value of displacement in the road profile. Later, this difference in amplitude will not matter anymore since the altitude at which the vehicle is travelling does not influence the behaviour of the suspension, only when the displacement changes there will be an effect. When comparing the LsAng profile (more precisely, the average of the left, middle and right wheel path) to the Pitch profile, there are some significant differences for both data sets. The Pitch profile has considerably high amplitudes, sometimes up to 60 cm which suggests a huge road bump (or a deep hole when the profile is negative, obviously). Simply from this it can already be seen that the road profile is not incredibly realistic or precise. The LsAng profile on the other hand is much smoother and the changes are not as rapid, and therefore much more realistic. Besides that, it can also be seen that again that some of the peaks match. The graphs for both data sets can be seen in appendix H. For completeness, also the graph for the Acc profile is shown in appendix I, however it is clear that this profile strongly deviates from reality as there are peaks as high as 16000 m. The same goes for the calculated IRI values for this Acc profile, which are shown in appendix K. Again, these values are way too high to be realistic. A different picture is drawn when comparing the Pitch and the LsAng IRI values. In both data sets, these values are almost identical and only deviate slightly. Most of the maximums overlap, and also the amplitudes barely deviate except in some cases. In appendices N and O, Scatter plots can be found which give a better overview of the results by showing the ground truth LsAng_IRI (both the left and the right wheel path) on the X-axis, and the measured value Pitch_IRI on the Y-axis. It can be seen that most measured values are below 5 m/km, and are in most cases lower than the true values.

The results for the standard deviations and the 95% confidence interval can be seen in table 1. The ratios in this table represent the values of the Pitch method that fall into the 95 % confidence interval (so between LsAngL/R +/- 2.82 * Standard deviation). These ratios show that actually not all values from the Pitch method lie within these intervals, the lowest being 82 % accurate and the highest being 93 % accurate. In order to further analyze whether the Pitch method is applicable, the averages of all IRI values were calculated, together with the confidence interval. These are shown in table 8. What can be immediately seen is how big the confidence interval actually is. That would mean that values up to 8 or 9 m/km would still be accepted as an average, even though the true value lies somewhere between 2 and 3 m/km.

	Dataset 1	Dataset 2
LsAngL Standard deviation	2.0311138518	1.6712859436
LsAngL Ratio of correct values	0.866442953	0.9369127517
LsAngR Standard deviation	2.1830612791	1.8379935406
LsAngR Ratio of correct values	0.8228187919	0,9046979866

Table 1. Standard deviation of LsAngL/R for both data sets.

The graphs that visualize both the upper and lower limit of the 95 % confidence interval for both the left and the right wheel path, and for both data sets can be found in appendices L and M. These are included mostly for completeness, but it also shows that most values that exceed

	Avg	Pitch Avg	Lower limit	Upper limit
LsAngL D1	3.562	2.137	-2.139	9.264
LsAngR D1	3.666	"	-2.425	9.758
LsAngL D2	3.498	2.289	-1.279	8.275
LsAngR D2	3.615	"	-1.569	8.798

Table 2. This table shows the averages of all data sets, together with the lower and upper limits for the 95 % confidence intervals.

the interval are where local maximums appear.

Another experiment that was conducted was verifying the mechanical modelling to confirm that the LsAng IRI values were calculated with the same method as the Acc and Pitch IRI values. These graphs can be seen in appendices P and Q, and they show that there are some differences in the model, but overall it produces very similar results. For a better visualization, scatter plots for the verifying the Pitch_IRI values are shown in appendix R.

9. DISCUSSION

It was already expected that the Acc method produces poor results, and confirms the notion already mentioned in the Roadscanners manual. One reason for that might be that the speed was not sufficiently high or was changing to rapidly. Starting and stopping the vehicle also cause the vehicle to move up or down, but does not indicate higher road roughness. Another reason might be a so-called "Integration shift" (see XSens 2021) that occurs when integrating velocities to calculate displacements or positions. The IMU manufacturer XSens[4] themselves has mentioned that this is a general issue with IMUs, and one should therefore not use IMUs for positioning. This further supports this claim.

On the other hand, the Pitch method is performing relatively well. The values for both wheel paths and data sets lie mostly within the allowed range of values. For the CROW certificate however, the accuracy might not be high enough when determining the intervals for all values. When taking the average, the value is definitely within the boundaries.

Interestingly, it produced the same IRI values even though the road profiles were significantly different. Reasons for that might be differences in the mechanical modelling or filtering. Another reason for that might also be that the values included in the output files are not exactly those that were used to calculate the road profile, but rather accumulated or unfiltered values. The difference in mechanical modelling is supported by the fact that the modelling conducted in this research did not produce the same results as the *Road Doctor* software. It is not entirely clear whether this is actually caused by a difference in modelling, or rather that the highly detailed road profile that is actually used in the calculations is hidden from the user, while the one in the data set is simply a filtered or integrated/accumulated version of the road profile.

10. CONCLUSION

From the experiments, it can be seen that IMU data nowadays is sufficient to provide a precise estimation of the road profile, and hence, also the IRI values. Thus, it should be not difficult to achieve a certification by the CROW organization. The Acceleration method however should be completely discarded due to the low accuracy. Alternatively, the LsAng data in combination with the Python scripts might be used to give an even more accurate representation of the road profile. This would require more implementation and polishing of the methods, since using the script is not very user-friendly and will take some time to produce correct values. Also, the mechanical modelling would need to be implemented or would needed to be done in 20-sim or Simulink.

Coming back to the research questions in section 1.2, it can be seen that they have been answered in this research. The two methods implemented by *Roadscanners* in their software *Road Doctor* were explained, some details however remain unclear, such as what filters have been used, and how exactly the mechanical modelling was implemented. But it was shown that the Pitch method produces precise and accurate results that are sufficiently close to the ground truth. Also the requirements by the Dutch authorities were investigated, and it was shown that the method could be certified according to these regulations, and therefore be used in field work.

11. FUTURE WORK

Before acquiring the certification by the CROW organization, it should be verified by Infrafocus whether the XSens IMU sensor fulfills the requirements mentioned in section 5.1. Since the information about these sensors was not available during writing, and also since this research focuses more on evaluating the end result computed from this method, this was not investigated and needs to be done by Infrafocus. When this has been verified, the next logical step would be to apply for the CROW certification procedure, and participate in it.

With regards to the LsAng method, there can be some further improvements made to increase the precision even more. Different filtering techniques might be applied instead of a simple moving average, to remove mechanical effects of the suspension such as oscillation after a road bump, possibly by applying a Fast Fourier Transformation or a different kind of low pass/high pass filter in order to remove certain frequencies such as the Natural frequency (sometimes referred to as Eigenfrequency) of the suspension system. Of course, it could also be investigated whether this oscillation even has an effect on the measurements and the calculations, or if modern suspension and damping systems already handle this issue. After all, if there is a lot of swinging after a speed bump, it is usually a sign that the suspension needs to be replaced because it is too old or broken.

Another thing that needs to be improved is the Python script for handling the LsAng data, since it needs vast amounts of memory in order to work. This is an easy fix however, since the labels simply need to be removed. This would however mean that all functions that access these labels now have to access the values by an index (so an integer pointing to the correct entry), and therefore need to be rewritten. Since this is only a proof-of-concept and not intended to be a final product, this was not part of this research.

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APPENDIX

A. PYTHON: PARSING TXT TABLES

```
def parseTxt(filename):
    # Initialization
    colNames = None
    data = []

    # Open file and read line per line
    with open(filename,"r") as f:
        for line in f:
            # Items in each line are separated by tabs
                (also remove new line and carriage
                return characters)
            splitLine =
                line.replace("\n","").replace("\r","").split("\t")

            if colNames == None:
                # First line that contains the column
                    names
                colNames = splitLine
            else:
                # All the other lines contains the
                    values
                obj = {}
                for headerIndex in range(len(colNames)):
                    if splitLine[headerIndex] == "":
                        # No value for this cell
                        obj[colNames[headerIndex]] = None
                    else:
                        obj[colNames[headerIndex]] =
                            float(splitLine[headerIndex])
                data.append(obj)

    return data
```

B. PYTHON: SORTING ENTRIES BY TIMER

```
def sortByTimer(filename):
    # Parse file
    data = parseTxt(filename)

    # Sort data by timer
    return sorted(data, key=lambda x: x['Timer(ms)'])
```

C. PYTHON: CALCULATING ROAD PROFILE FROM LASER SCAN

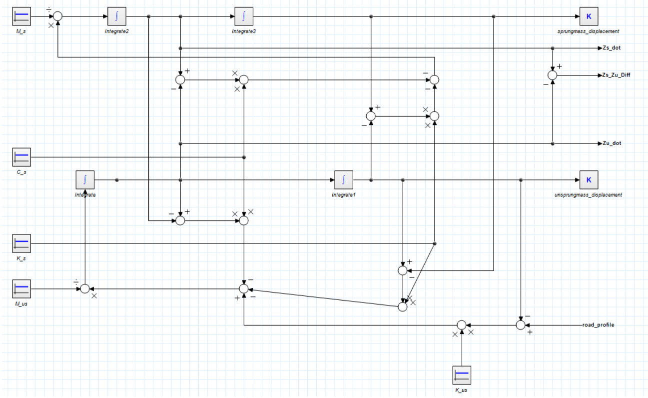
```
# Return the degree of the measurement with the
    lowest distance
def get_degree_of_min_dist(lsAng, i):
    curr_min_key = None
    curr_min_val = math.inf

    for A_k in [k for k in lsAng[i] if "A_" in k and
        not lsAng[i][k] == None]:
        if lsAng[i][A_k] < curr_min_val:
            curr_min_key = A_k
            curr_min_val = lsAng[i][A_k]
    return (curr_min_key, curr_min_val)

# Return the degree closest to the parameter 'deg' of
    laser scan data 'lsAng', row 'i'
def get_degree_closest_to(lsAng, i, deg):
    curr_min_key = None
    curr_min_val = math.inf

    for A_k in [k for k in lsAng[i] if "A_" in k and
        not lsAng[i][k] == None]:
        if curr_min_key == None or (abs(deg -
            float(A_k.split("_")[1].replace("(m)","")))
            < abs(deg -
            float(curr_min_key.split("_")[1].replace("(m)","")))):
            curr_min_key = A_k
            curr_min_val = lsAng[i][A_k]
```

```
    return (curr_min_key, curr_min_val)

# Calculate road profile for laser scan data and
     write to file
def road_prof_lsAng(lsAng):
    with open("Python
         Output\RoadProfile_LsAngLMR.txt","w") as f:
        # Write header
        f.write("Timer(ms)\tDiffLoc(m)\tRoadProfileL(m)"
             + \
             "\tRoadProfileM(m)\tRoadProfileR(m)\n")

        first_Loc = None

        # Go through all measurements and calculate
             time and road profile
        # Skip the first one, it only contains the
             sensor configuration
        for i in range(1,len(lsAng)):
            # Get the value for approx. 90 degree, and
                 of the left and right wheel path
            _ , minDist_val_L =
                 get_degree_closest_to(lsAng, i, 75.39)
            _ , minDist_val_M =
                 get_degree_closest_to(lsAng, i, 90.0)
            _ , minDist_val_R =
                 get_degree_closest_to(lsAng, i, 104.61)

            if first_Loc == None:
                f.write("0.0\t0.0\t0.0\t0.0\t0.0\n")
                first_Loc = lsAng[i]['Loc(m)']
            else:
                # Calculate travelled time and how long
                     it would take when driving at 80
                     km/h
                travelled_dist = lsAng[i]['Loc(m)'] -
                     first_Loc
                timer = travelled_dist / 8 * 360

                # Calculate road profile
                road_prof_L =
                     math.sqrt(lsAng[0]['CElev(m)']**2
                     + 0.8**2) - minDist_val_L
                road_prof_M = lsAng[0]['CElev(m)'] -
                     minDist_val_M
                road_prof_R =
                     math.sqrt(lsAng[0]['CElev(m)']**2
                     + 0.8**2) - minDist_val_R

                # Write to file
                f.write(str(timer) + "\t" +
                     str(travelled_dist) + "\t" +
                     str(road_prof_L) + "\t" +
                     str(road_prof_M) + "\t" +
                     str(road_prof_R) + "\n")
```

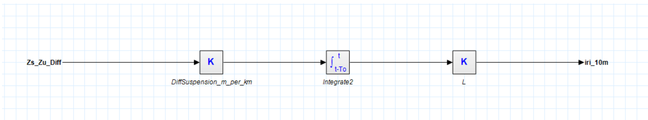
D. PYTHON: NORMALIZING ACCIRI FILE

```
# Add timer column to AccIRI files so that it can be
# used by 20-sim. Just like the other timer columns,
# it is given in milliseconds. Again, it resembles
# the time it takes to drive the travelled distance
# at 80 km/h, so that it is equivalent to the Golden
# Car simulation.
def normalize_Acc_Pitch_Prof(acc_iri):
    with open("Python
         Output\RoadProfile_AccIRI.txt","w") as f:
        f.write("Timer(ms)\tFrom\tTo\tAcc_Prof\t" + \
        "Acc_IRI\tPitch_Prof\tPitch_IRI\n")

        timer = 0.0

        for a in acc_iri:
            travelled_dist = a['To'] - a['From']
            duration_ms = travelled_dist / 8 * 360

            f.write(str(timer) + "\t" +
                 str(a['From'])+ "\t" + str(a['To']) +
                 "\t" + str(a['Acc_Prof']) + "\t" +
                 str(a['Acc_IRI']) + "\t" +
                str(a['Pitch_Prof']) + "\t" +
                     str(a['Pitch_IRI']) + "\n")

            timer += duration_ms
```

E. 20-SIM MODEL: GOLDEN CAR MODEL

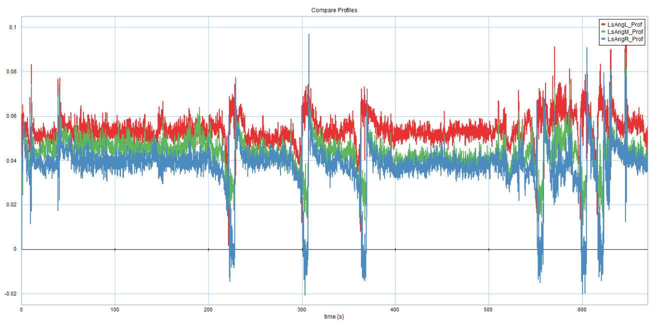


F. 20-SIM MODEL: IRI CALCULATION



G. GRAPH: COMPARING ROAD PROFILES BASED ON LASER SCANS FOR DIFFERENT WHEEL PATHS (LEFT, MIDDLE, AND RIGHT)

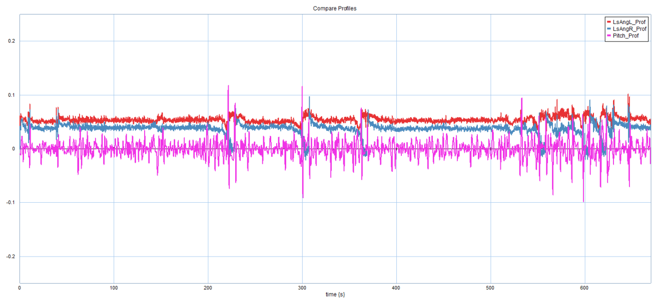
Data Set 1



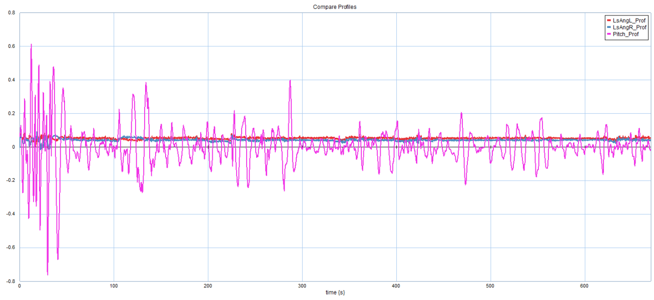
Data Set 2

H. GRAPH: COMPARING LSANG_PROF AGAINST PITCH_PROF

Data Set 1

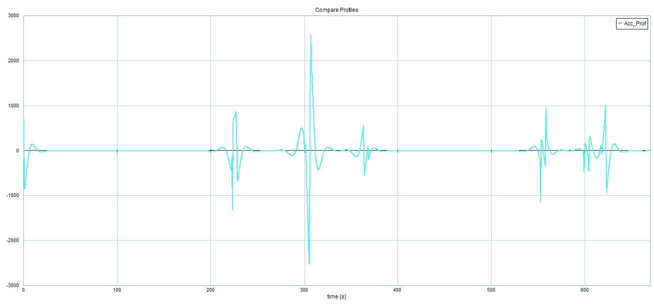


Data Set 2

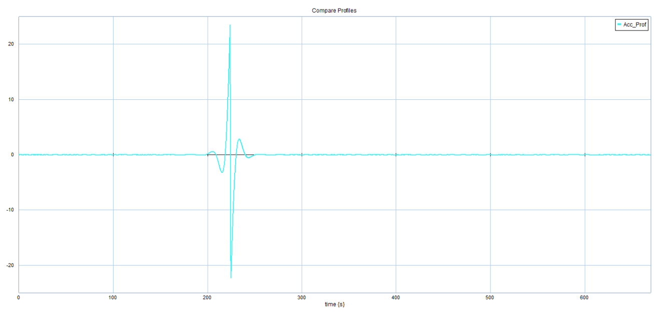


I. GRAPH: ACC_PROF

Data Set 1

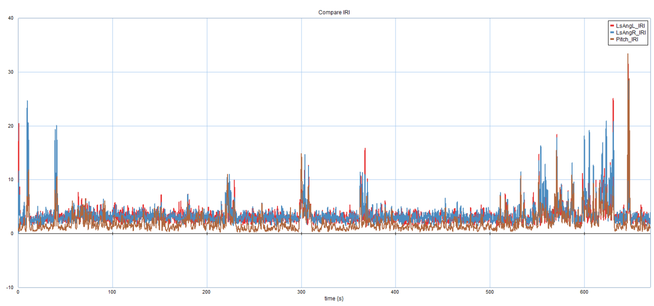


Data Set 2

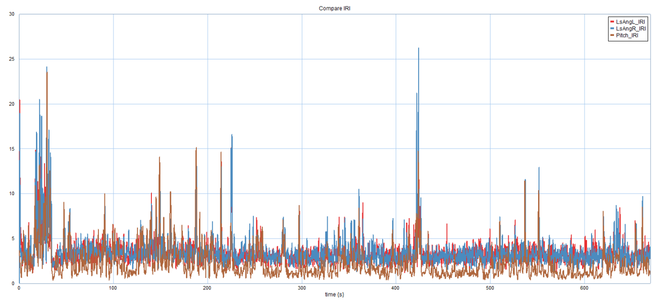


J. GRAPH: COMPARING PITCH_IRI AGAINST LSANG_IRI

Data Set 1

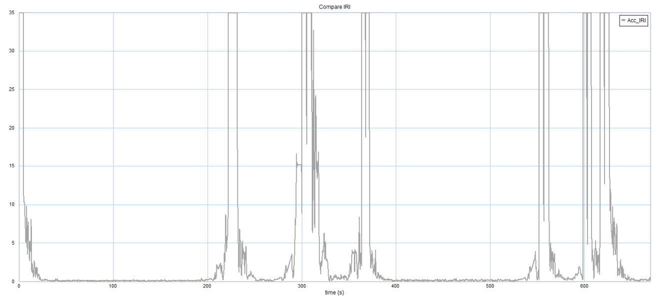


Data Set 2

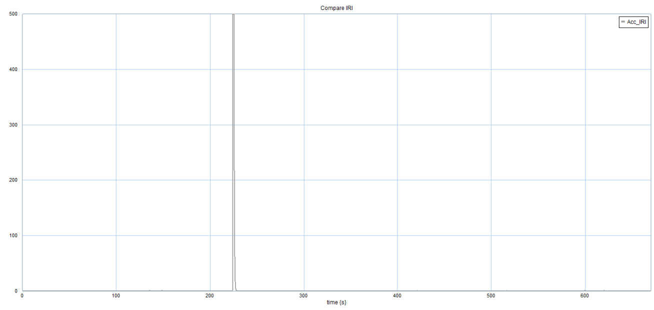


K. GRAPH: ACC_IRI

Data Set 1

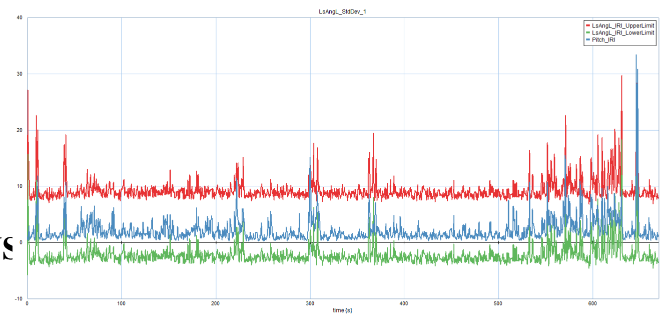


Data Set 2

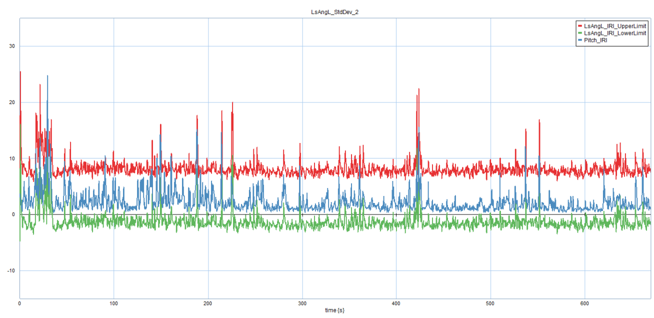


L. GRAPH: LSANGL STANDARD DEVIATION

Data Set 1

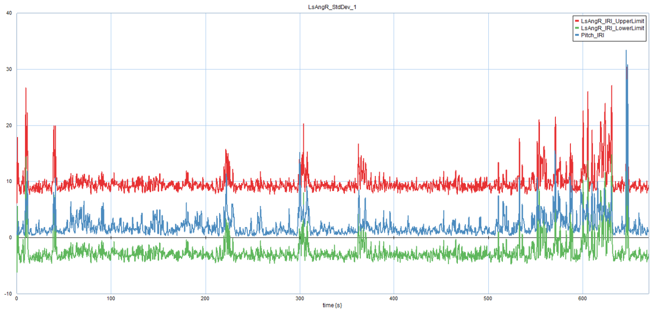


Data Set 2

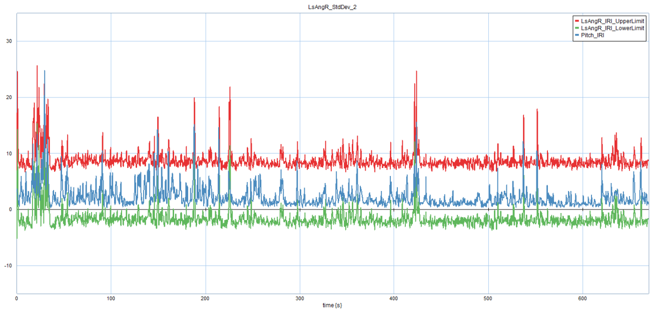


M. GRAPH: LSANGR STANDARD DEVIATION

Data Set 1

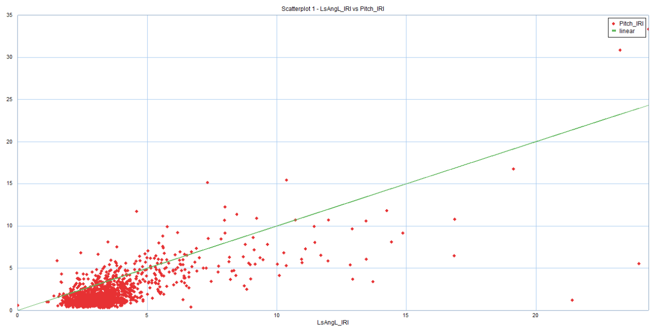


Data Set 2

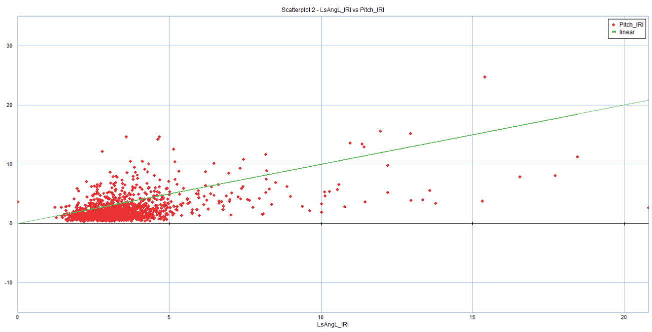


N. SCATTERPLOT: COMPARISON LSANGL_IRI AND PITCH_IRI

Data Set 1

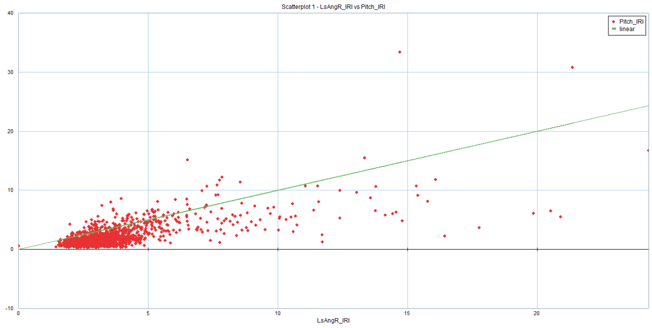


Data Set 2

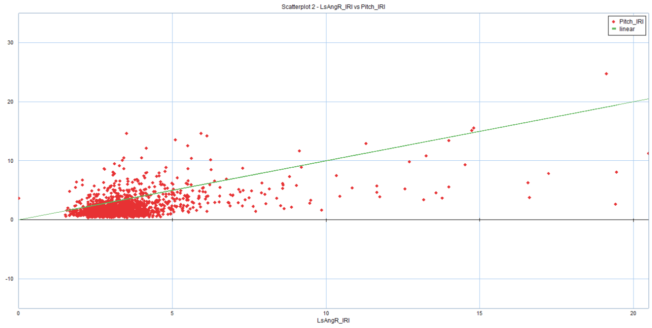


O. SCATTERPLOT: COMPARISON LSANGR_IRI AND PITCH_IRI

Data Set 1

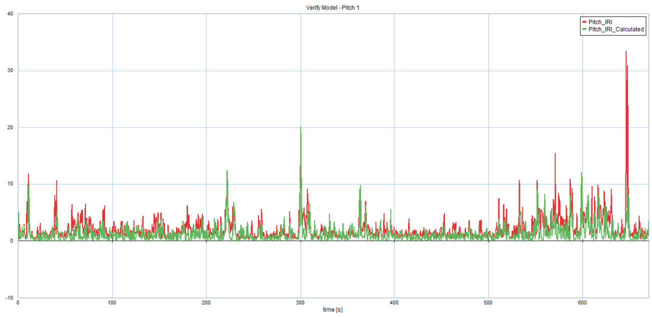


Data Set 2

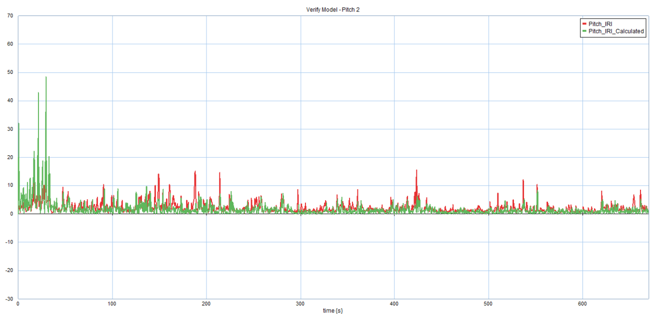


P. GRAPH: VERIFY MECHANICAL MODEL - PITCH

Data Set 1

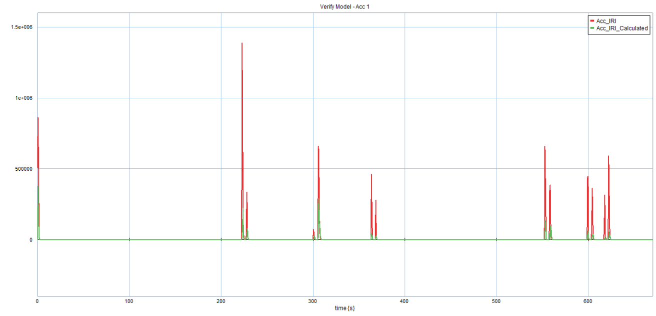


Data Set 2

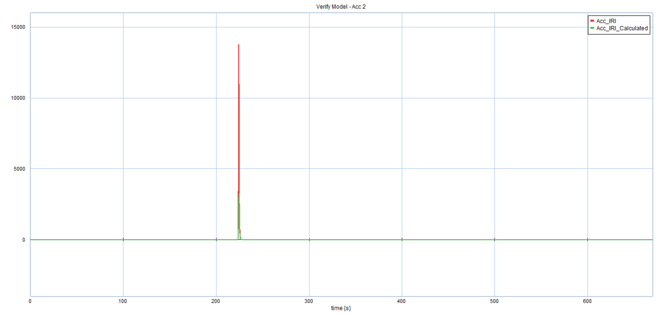


Q. GRAPH: VERIFY MECHANICAL MODEL - ACC

Data Set 1

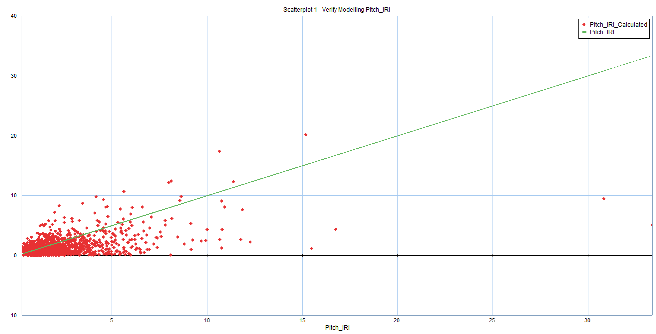


Data Set 2



R. SCATTERPLOT: VERIFYING MECHANICAL MODEL - PITCH_IRI

Data Set 1



Data Set 2