UKRAINIAN CATHOLIC UNIVERSITY

BACHELOR THESIS

Detecting conditions that cause unstable sensor road test readings: using Quality Control Charts

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Declaration of Authorship

I, Alina VOROBCHUK, declare that this thesis titled, "Detecting conditions that cause unstable sensor road test readings: using Quality Control Charts" and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
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- I have acknowledged all main sources of help.
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Date:

"Develop a passion for learning. If you do, you will never cease to grow."

Anthony J. D'Angelo

UKRAINIAN CATHOLIC UNIVERSITY

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Detecting conditions that cause unstable sensor road test readings: using Quality Control Charts

by Alina VOROBCHUK

Abstract

Road infrastructure plays a significant role in a country's economic development. To maintain this vital infrastructure, road maintenance and preservation are extremely important.

Weigh-in-motion (WIM) technology is a practical and economic solution to mitigate some of the consequences of road deterioration. While WIM systems have a number of advantages; their main drawback is the measurement accuracy. The quality of the sensor readings is highly dependent on different environmental factors, which may cause anomalous values in data.

My thesis focuses on detecting abnormal sensor values and identifying the reasons that caused such sensor readings. This paper examines the effectiveness of applying the Quality Control Charts for detecting abnormal sensor values in WIM tests.

The project aims to provide recommendations that help understand the features and limitations of road sensors in various environmental conditions. Furthermore, this work can serve as a basis for further studies in the field of road construction.

Acknowledgements

First of all, I would like to express sincere gratitude to my supervisor, Renata Konrad for her constant support and help at every step of my work. I am thankful for all the valuable advice and ideas, and for the motivation to work on my diploma.

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For all those who helped and encouraged me during all my studies…

Chapter 1

Introduction

1.1 Road system in Ukraine

In recent years, many processes in Ukraine have changed, and considerable reforms have been implemented in different spheres for the country's growth and development, including infrastructure. Road infrastructure is a crucial asset for society. However, many roads in our country were in poor condition.

One of the main reasons for the deterioration of Ukrainian roads is traffic in excess of dimensional and weight parameters. Overloaded trucks have a great impact on road and bridge durability. According to scientific research and road infrastructure experts, the adverse effect of each overloaded truck on the road surface grows exponentially with its weight per axle. (*Ukraine opts for Kistler Lineas WiM sensors* n.d.[a])

Apart from severe road damage, heavily overloaded vehicles also present a serious safety hazard, as the braking distance of an overloaded truck could be twice as long compared to a vehicle loaded according to regulations.(*Ukraine opts for Kistler Lineas WiM sensors* n.d.[b])

One more reason for road deterioration in Ukraine is the war. Ukraine suffered, and continues to suffer, significant damage to its infrastructure, including roads and bridges, as a result of Russian hostilities and rocket fire. On the 62-nd day of war, Andriy Ivko, First Deputy Head of Ukravtodor, the State Agency for Highways of Ukraine, stated that due to the Russian aggression, more than 23,000 km of roads have already been damaged or fully destroyed, representing over 13% of the total road length in the country. As a result, Ukravtodor is ready to restore all roads and bridges as soon as possible, and the government agency is already preparing different project documentation for restoration.(*13% of Ukrainian roads destroyed due to the war, says Ukravtodor* n.d.)

However, even before the Russian invasion, the rapid decay of road surfaces has long been a significant issue for Ukravtodor. Pavement wear, cracks, potholes, and other types of road damage were a common sight, especially on major Ukrainian transport routes.

The former Minister of Infrastructure in Ukraine - Vladislav Krykliy - said that one of the priorities of road infrastructure should be not only the construction of roads but also their preservation. In this way, an immediate cause of the road destruction problem could be overcome, not only the consequences. Strengthening weight control can be an effective way to greatly reduce road damage, especially by automating weighing processes.(*WiM* n.d.)

For this reason, the implementation of measures aimed at preventing weight and size violations on Ukrainian roads is needed.

1.2 Weigh In Motion Technology

Weigh In Motion (WIM) technology is the best solution of choice for traffic monitoring, weight enforcement, and weight-based tolling. (*Weigh-in-Motion* n.d.) Weighing In Motion is the process of measuring the dynamic tire forces of a moving road vehicle and estimating the gross-vehicle weight and the portion of that weight carried by each wheel, axle, or axle group of a corresponding static vehicle in real-time.(Loo, n.d.[b]) In addition, several types of WIM can be applied in different situations, depending on the needs and purposes of use. Currently, the following WIM types are in use: low-speed WIM (LS-WIM), high-speed WIM (HS-WIM), Bridge WIM (B-WIM), and On-Board WIM (OBW).(Loo, n.d.[a])

WIM systems can improve the effectiveness of the weighting control since, unlike the static scales, a great benefit of WIM is that the sensors of the system can measure the weight and gather data about certain characteristics of the vehicle while it is traveling at a reduced or normal speed. This results in a greater number of vehicles that could be weighted during the day. The system also allows for both the possibility to view data in real-time as well as to store it for future analytics. Furthermore, WIM is an automated weighing system, thus, reducing opportunities for corruption for ill-intended users.

To collect and store all the needed vehicle attribute measurements, a set of weighing sensors is: mounted on the pavement; attached to a bridge; or installed directly on the vehicle, depending on the WIM system type. That's why gathering weight-in-motion data is very useful for evaluating the state of infrastructure and can help to better plan the maintenance of the roads and bridges. However, because of the environment in which the sensors perform, the quality and lifespan of the system are significantly affected by specific conditions such as weather, and soil type - some of which change not only seasonally but also daily.(Burnos and Gajda, 2020a)

1.3 Issues with WIM Measurement Accuracy

The main issue of the WIM system implementation is the accuracy of the weight measurements. The accuracy of weigh-in-motion data is generally much less compared to static weight scales where environmental factors are better controlled.(*Weigh-in-Motion – Pavement Interactive* n.d.)

Since the WIM sensors are mostly installed directly on the road pavement, the quality of measurements highly depends on numerous conditions such as pavement temperature changes, quality of the road surface, wind, humidity, vehicle speed, and some others.

Therefore, to ensure the proper operation of the system, various measures should be applied, including measurement quality checks, and sensor serviceability review. Currently, several methods help to identify a malfunction of the WIM systems and adjust the measurements considering different interfering factors and constructions of the sensors. These methods are applied to overcome the instability of the system and increase the effectiveness of the weight controls of the trucks using WIM.

To provide the required accuracy level of WIM, the systems need to be periodically calibrated. The basic and most commonly used methods of calibration are: calibration with standard weights, calibration with specific devices, calibration with pre-weighed vehicles (test vehicles), and autocalibration. But still, these methods may not always be able to fully ensure accurate data reading by sensors.(Gajda, Sroka, and Burnos, 2021)

1.4 Project Contribution

Problem Statement

WIM systems have been shown to be extremely beneficial, as they can be used not only for imposing weight and size restrictions on the vehicles but also for monitoring and designing bridges and pavements and assisting in the planning of maintenance works.

However, before installing the sensors, it is important to understand all the constraints and factors that can cause inaccurate readings. In turn, accurate readings will create a situation that produces more accurate analysis results.

Since unstable sensor reading and consequently the unreasonable values in data are common problems for the system performance, in my bachelor thesis, I decided to focus on detecting the anomalous values in sensor data and identify the reasons that caused such readings. This work is important because it will lay the foundation for further studies for Ukraine when installing WIM on rebuilt roads.

Project Goal

The aim of my study is to identify and analyze abnormal sensor data values and provide recommendations regarding the use of sensors in various environmental conditions. The results of the project are intended to help inform road planners in Ukraine so as to understand the limitations of WIM sensors.

Project Objectives and Report Structure

To achieve the goal of my work, I took six steps, each of which is described in the following structure and respective chapter:

Chapter 1. Introduction

As I wasn't familiar with the topic of truck weighting and WIM technology before, first of all, I needed to make great background research and get to know more about the features and the specifics of the road sensors' work. I also read a lot about the ways of calibration of the sensors and learned about the major problems of this process - that is presented in the first chapter.

Chapter 2. Related Works

To clearly understand how to solve the problem, I had to discover the existing approaches to the solution. An overview of the studies conducted by other researchers is described in the Related Works section.

Chapter 3. Data description

An essential step was to find the data related to my research, which was not an easy task. The description of the data I used for the analysis is provided in Chapter 3.

Chapter 4. Methodology

Exploration of the methods that can be used to recognize the abnormal readings was an important part of my work. The chapter describes different types of Quality Control Charts and the reasons why I used them to develop my analysis.

Chapter 5. Analysis

The Chapter describes the steps of the developed analysis and lists some findings on the quality of performance of the road sensors in various conditions.

Chapter 6. Conclusions

The Conclusions Section describes the results of the study. Also, we list the steps that can be done to improve the work.

Chapter 2

Related Works

As mentioned previously in Section 1.3, WIM sensors require occasional calibration. The autocalibration method is becoming more popular nowadays. The method consists of continuous estimation of the WIM system calibration coefficient and modifying the weighing results according to the currently specified estimate.

A great contribution to this field was made by Piotr Burnos, who conducted a significant amount of research and experimentation in this area. His works mostly focus on the analysis of the autocalibration algorithms, assessing their accuracy, and present the optimization of autocalibration algorithms that can further be used for direct mass enforcement. (Burnos and Gajda, 2020b; Burnos, 2012)

It should be also noted that in all the works, that are related to WIM, the vast majoring of research is regarding the factors that may influence the sensors and interfere with their accuracy, and this is the part I want to pay attention to in my bachelor thesis.

A relevant work to my research is that of Raz et al (2004)(Raz et al., 2004), in which the authors assessed the quality of the gathered data. They used the monitoring data from WIM sensors that were collected by the Minnesota road research project (Mn/ROAD). The data consisted of over three million observations for ten commercial vehicle types out of fourteen total vehicle types. Each observation has attribute values for a single commercial vehicle: date and time (accurate to the millisecond), vehicle type (one of ten classes), lane (one of two classes), speed (mph—miles per hour), error code (one of the twenty-five classes), length (feet), ESAL, number of axles, and weight (kips-kilo-pounds). The authors propose a data mining approach and an automated method for helping a user in creating a model of proper data behavior. Their predicate inference framework uses the expectations of the user for the data behavior to detect semantic anomalies in that data. As the proposed approach is automated, it detects anomalies very quickly.

As for my work, I used the data that was collected by the same research project mentioned above. It should be noted that, as in the previous paper, I also look for the anomalies in the data, but with the help of Quality Control Charts rather than with data mining and machine learning algorithms. My contribution is to evaluate the effectiveness of this method in identifying abnormal data readings. Furthermore, after identifying the out-of-control points, I sought to determine what could cause abnormal measurements.

Chapter 3

Data Description

3.1 Ukrainian Data

As of February 2022, there were 52 WIM systems located along the highways in different regions of Ukraine.

The full range of work on the implementation of the Weigh-in-Motion technology was carried out by the "SEA" company. The company provided the design, manufacture, and development of the sensors. They also supplied, and installed equipment and supporting structures, as well as were responsible for technical support of WIM systems and designing a web interface for Ukravtodor. The data from WIM systems are collected and processed by Ukrtransbezpeka - the State Service for Transport Security.(*WIM SEA* n.d.)

Data from WIM systems include time, date, vehicle speed, vehicle axle count, axle spread, axle weight, gross vehicle weight, vehicle classification, vehicle number plate, and the total length of the vehicle.(*Weigh-In-Motion (WIM) | Caltrans* n.d.)

Initially, I planned to use this data for my analysis, but because of the current situation in Ukraine, this data was not made available. Attempts were made until the end of April to secure this data, but I was unable to do so. For this reason, I had to identify alternative suitable data sources that could serve as a proxy for my area of study.

3.2 Alternative Source of Data

The data that I used for my research was open-source data that was collected by the Minnesota road research project (Mn/ROAD) and the Long Term Pavement Performance (LTPP) Project (LTPP 1999), and it is owned by the Minnesota Department of Transportation.(*LTPP InfoPave - Overview* n.d.)

MnROAD works with MnDOTś Materials & Road Research Lab. Using the tests and analysis of the Lab, together the two organizations attempt to find ways to make roads perform better, last longer, and reduce the impact of the environment on the road surface.

MnROAD is a pavement test track that includes two roads which are located near Albertville, Minnesota:

FIGURE 3.1: MnRoad

- A 3.5-mile mainline interstate roadway carrying 'live' traffic averaging 28,500 vehicles per day with 12.4 % trucks.
- A 2.5-mile closed-loop low-volume roadway carrying a controlled 5-axle tractor-semi-trailer to simulate conditions of rural roads.

Besides two main test roads, the MnROAD system monitors and evaluates the measurements on some other roadways' test sections.

The test roadways also have over 75 unique test 'cells', which are made up of various materials and pavements and are used to explore their performance, which is monitored by sensors within the road structure.(*MnROAD Home - Materials & Road Research - MnDOT* n.d.)

3.3 Data fields

A file 'MnROAD_Aggregate.xlsx' contains aggregate testing information, including traditional test results. These results were obtained from 27 different kinds of laboratory tests. Of the 27 types of tests used, the file contained information about the date of the test, the material group that was used during the investigation, the section ID and cell the test was held in, and some other information.

Soil aggregates and their quality are of great importance for any road construction, maintenance, and possible deterioration. Road experts have to be confident that the pavement structure will be able to withstand vehicle weight and pressure on it. That is why, to ensure the strength and reliability of the soil, soil aggregates tests are required to be performed.

The most important and commonly used soil tests are listed below.(*Soil Testing Required for Road Construction - Civil Engineering Forum* n.d.; *What Types of Soil Tests Required for Road Construction?* N.d.)

- **Moisture content**

  Determine the moisture content of the soil is required almost for all soil tests. It is expressed as the percentage of water in the soil to its dry mass.

The moisture content in soil signifies the various properties of soil, such as compaction, permeability, particle size, etc. Moreover, the knowledge about moisture content will give an idea of the state of the soil.

- **The specific gravity of soil**

  The knowledge of specific gravity is needed in the calculation of soil properties like void ratio, degree of saturation, etc. It is the ratio of the weight of soil in the air of a given volume at a standard temperature to the weight in air of an equal volume of distilled water at the same stated temperature.

- **Particle Size Distribution**

  Particle size distribution, also known as gradation, refers to the proportions by dry mass of a soil distributed over specified particle-size ranges. What is more, data from the gradation test is often used to determine the suitability of soil that then is needed for road or airfield constructions.

- **Compaction test - Proctor test**

  This soil compaction test, also known as Proctor test, is used to determine the mass of dry soil per cubic meter when the soil is compacted over a range of moisture contents, giving the maximum dry density at optimum moisture content. Thus this test provides the compaction characteristics of different soils with changes in moisture content.

- **California Bearing Ratio (CBR) Test**

  The CBR test is used for the evaluation of the subgrade strength of roads and pavements. The CBR value obtained by this test is used with the empirical curves to determine the thickness of pavement and its component layers. This is the most widely used method for the design of flexible pavement.

Chapter 4

Methodology

A variety of methods exist and are used for anomaly detection in data. Many current methods rely on complex machine learning algorithms. However, these methods are usually costly to develop, hard to explain, and require special skills. For these reasons, my thesis investigates the effectiveness of using a simpler method as a good approximation.

Quality Control Charts is a very powerful tool that can help discover the out-of-control points within the data, observe patterns, make some assumptions or even predictions for the future performance, identify problems of the current process and generate ideas for the possible solutions. For these reasons, I decided to develop my analysis using the Quality Control Charts and thus checking their performance.

4.1 Overview of Quality Control Charts

A Quality Control Chart is a statistical process chart that assists in understanding the quality of the products as well as showing how the process changes or improves over time and finding out the deviations from the normal value ranges in the data. Control Charts are also called Shewhart charts after an American Physicist and statistician, Walter Andrew Shewhart, who developed them. The charts are very easy to implement and understand.(*Control Chart: A Key Tool for Ensuring Quality and Minimizing Variation | Lucidchart Blog* n.d.; *Control Charts* n.d.)

The main elements of the quality control charts are:

1. Graph with data points of specific time intervals;
2. A horizontal central line for the visualization of the mean;
3. Horizontal lines represent upper and lower control limits, which are usually equal to +3 and -3 standard deviations from the average. Out-of-control points in the data can be determined by comparing the data to these control limits.

4.2 Variation types

Dr. Shewhart discovered and reported that there are different types of variation within the processes: common cause variation (also called normal process variation) and special cause variation. The quality control charts are used to graphically separate these two types of variation and help to distinguish them easily.

Common cause variation is always present in data and is caused by unknown factors. In statistics, such a type of variation is usually called inherent variation or noise.(*Common Cause & Special Cause Variation Explained with Examples – Knowledge Hub for Business Management and Technology Professionals* n.d.)

Special cause variation is referred to as such that hasn't been previously observed, is unpredictable and uncontrolled, and can represent the anomalies in data.

Such variations can be easily recognized on the control charts, where they are displayed as the out-of-control limit points.(Team, n.d.) These are the points that are important to identify for this thesis.

4.3 Types of Quality Control Charts

There are many various types of Quality Control Charts, and to analyze data, it is essential to select the correct one. The control charts are determined by the data type(discrete or continuous) and sample size. In the case that data is discrete, the following are applicable: C-chart, u-chart, p-chart, and np-chart. If the event data is continuous, such as the case with WIM data, the following tests are applicable:

- x-bar chart along with R(the range grand mean) chart is used when the sample size is greater than 1 and less than 11
- s chart (the standard deviation grand mean) is used with the x-bar chart when the sample size is greater than 10 units.
- mR (moving range grand mean) chart can be used with an individual x chart if the sample size is equal to 1
  Regardless of sample size, each test observes the mean and variation of a process based on samples.(*Quality Control Charts with Python | by Roberto Salazar | Towards Data Science* n.d.)

Chapter 5

Analysis

The first step in any data analysis should be data cleaning. The Mn/ROAD dataset used for this project was already cleaned as it is a source for researchers. It did not require much cleaning, and I only had to remove Nan values.

As mentioned previously in Chapter 3, performing soil tests is an essential step before constructing or maintaining a road. The dataset used included 27 types of road tests that were conducted on different soil material groups. As such, my project involved investigating the effectiveness of applying the Quality Control Charts to test results.

To draw insightful and actionable conclusions from the analysis, a sufficient number of observations for every kind of test are required as well as a wide range of time so that certain conclusions about the factors that influence sensor readings can be made.

For that reason, my first step in the analysis was to explore the distribution of the number of tests conducted during different periods of the year.

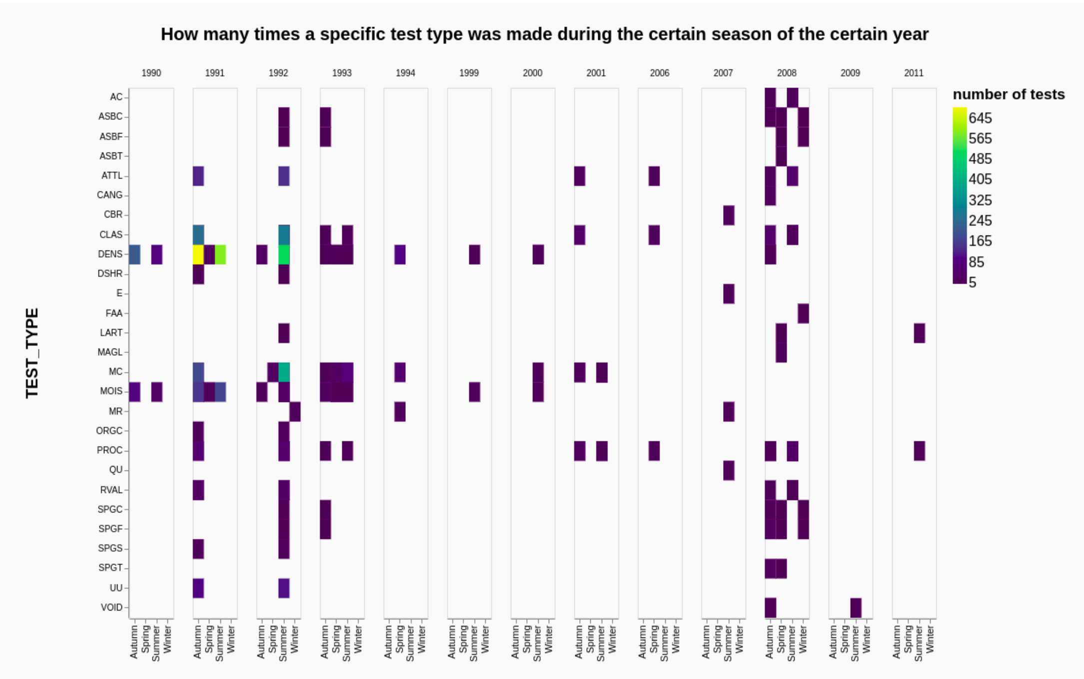

FIGURE 5.1: Distribution of the number of tests conducted during different periods of several years

From Figure 5.1 , we can see that the data used contains test results in the date range from 1990 to 2011, and observations from several years are missing. Moreover, we can notice that the majority of tests were performed in summer and autumn, and there are almost no data points for the testing results obtained in winter. Thus, such data lack makes it impossible to explore the effects of the severe frosts and snowfalls on the quality of soil and sensor readings.

My next step was to apply the Quality Control Charts to the test results values. Since my data consists of different road tests, each of which can be considered as a separate group, an x-bar chart along with an s chart have to be used in this case.

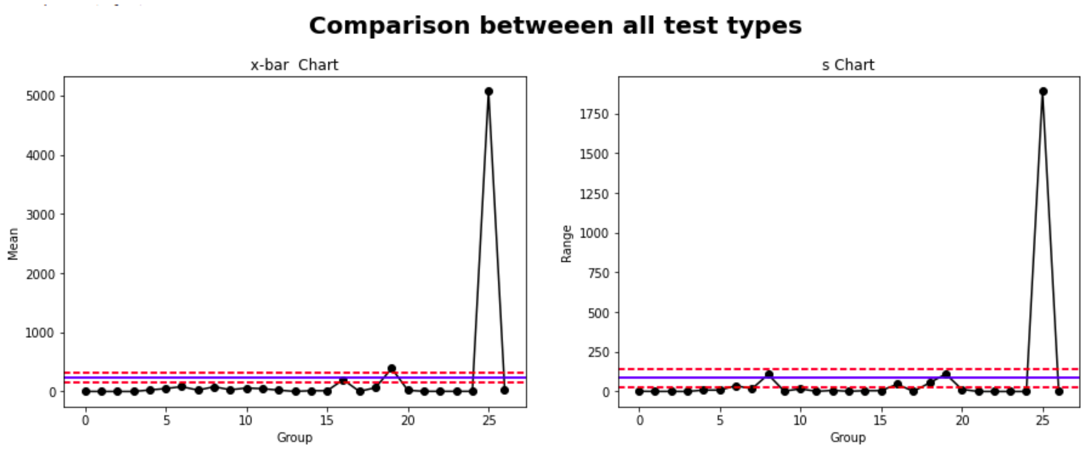

FIGURE 5.2: Comparison between all test types

From chart 5.2, we can clearly see that the average values within one of the test groups greatly differ from the values of the rest. For this reason, I decided to look closer at every test group and compare them. I realized that every test type has its own range of permissible values. Furthermore, most of them have different measurement units. That is why, the Quality Control Chart can not be used in such a situation, as it won't reveal any informative results. Consequently, every test type should be separately observed.

For an individual test type, an x chart along with an mR chart have to be used. Figures 5.4 and 5.4 are examples of charts for several of the test groups.

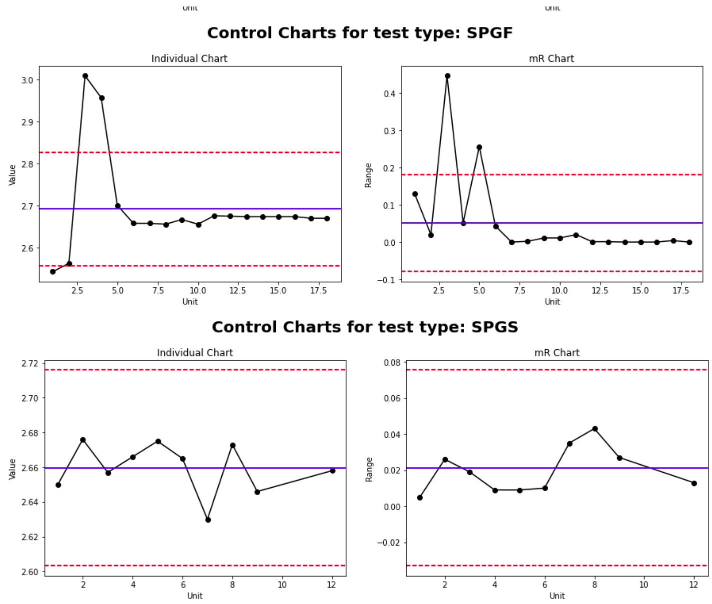

FIGURE 5.3: Example of Quality Control Charts

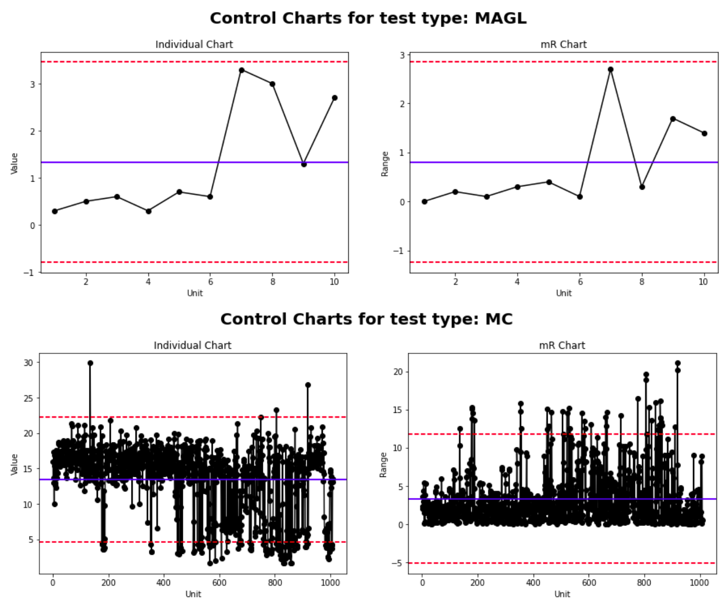

FIGURE 5.4: Example of Quality Control Charts

All the data points that lie out of the red lines, which are the lower and upper limits, are out-of-control points that can represent anomalous values. The examples above show that there are tests with all data points within the control limits, as well as those that have unreasonable values. Besides, we notice that some types of tests have only a few observations.
Table 5.5 below indicates the number of observations for each test type.

DENS	2903	SPGS	13
MC	1010	CANG	12
CLAS	970	CBR	12
MOIS	687	MAGL	11
ATTL	394	ASBC	8
PROC	368	SPGC	8
UU	210	E	6
RVAL	82	ASBF	6
MR	24	QU	6
SPGF	19	LART	5
AC	16	DSHR	5
SPGT	14	VOID	4
ORGC	13	FAA	2
		ASBT	1

FIGURE 5.5: Number of test observations

Because of the small number of observations for some tests, to have more robust results, I decided to explore only those tests with 100 or more observations to identify out-of-control points. These tests are: DENS, MC, MOIS, RVAL, and UU.
DENS reffers to a dry density road test. MC and MOIS are the types of tests that measure moisture content in the soil. RVAL stands for R-value, which measures the ability of the tested material to resist lateral spreading due to an applied vertical load.(Lauren, n.d.) UU is an Unconfirmed Compressive Strength, which calculates the maximum axial compressive stress that a specimen can bear under zero confining stress.(*Unconfined Compression Test | Geoengineer.org* n.d.)

Test results are likely highly dependent on the material that was used, as each soil (material) group has unique characteristics and features. Therefore, the next data attribute I wanted to research was the material group.

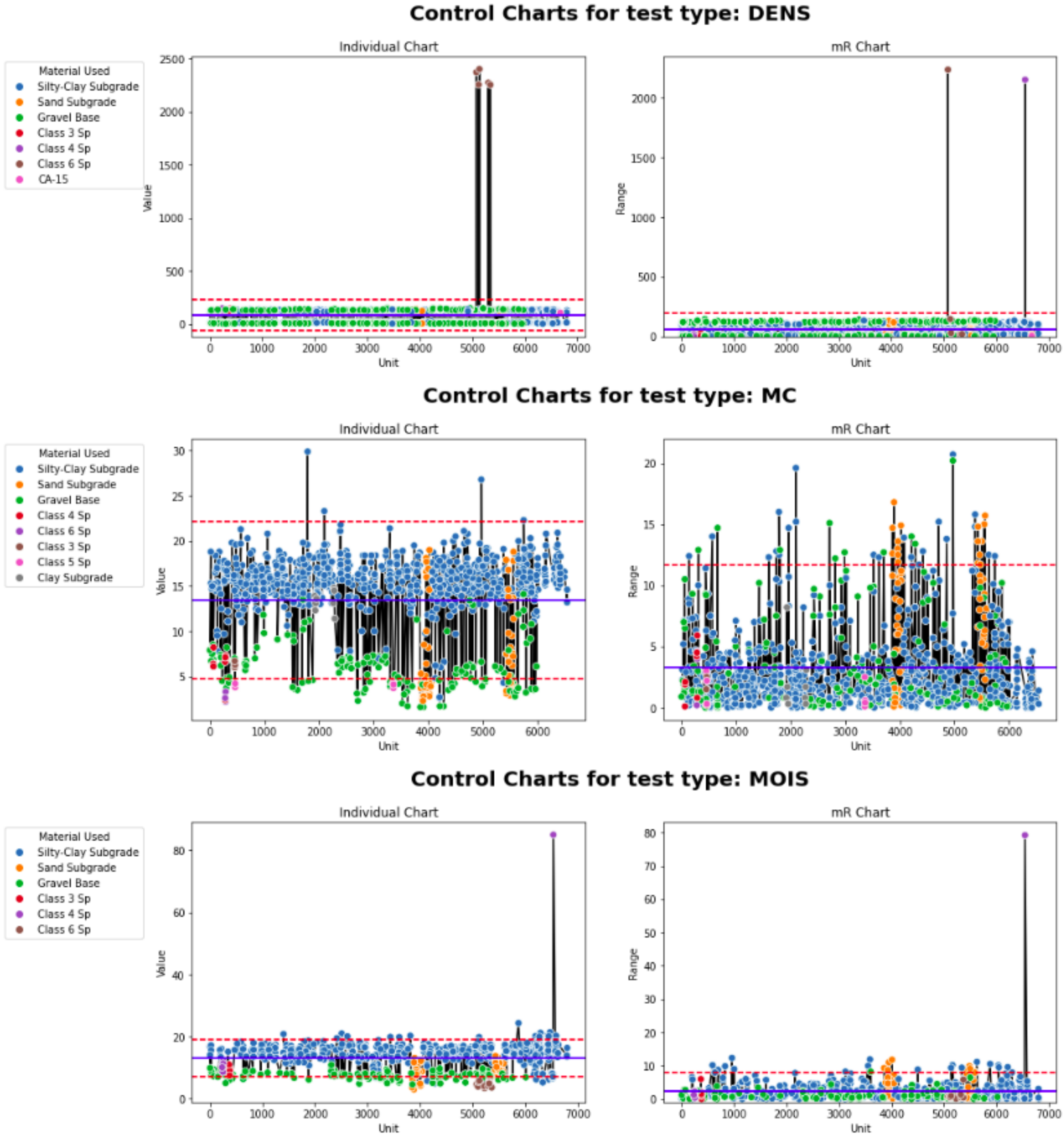

FIGURE 5.6: Quality Control Charts including material groups

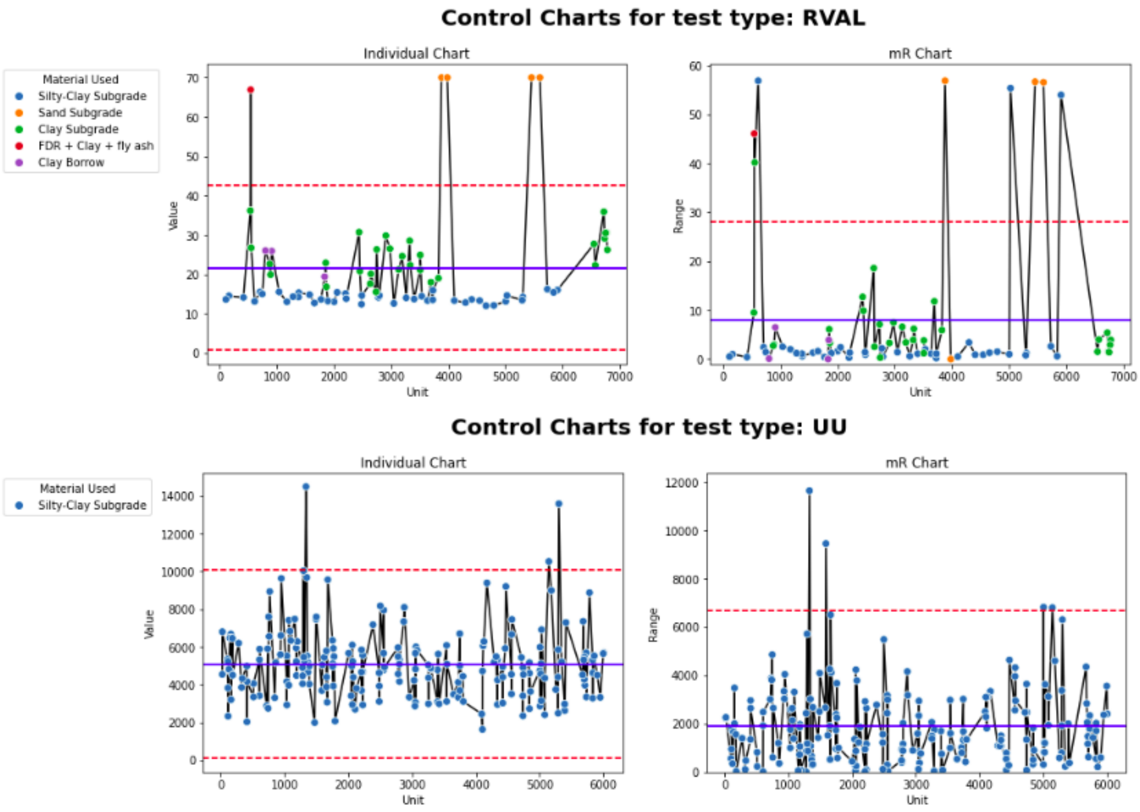

FIGURE 5.7: Quality Control Charts including material groups

From Figures 5.6 and 5.7, I found that certain tests have a common material group for some out-of-control values. For example, the Class 6 SP material group causes unreasonable values in 3 of the 5 observed test types.

For a better understanding of the performance of the road sensors on different materials, I created the following table (5.8):

	MATERIAL_GROUP	TEST_MAT_OUT	MATERIAL_LEN	PERC_OUT
0	Bituminous Aggregate	2	35	5.71
1	Bituminous Mix	6	26	23.08
2	Class 4 Sp	2	39	5.13
3	Class 5 Sp	8	20	40.00
4	Class 6 Sp	21	23	91.30
5	FDR (HMA + Cl 5)	1	2	50.00
6	FDR + Clay + fly ash	1	9	11.11
7	Gravel Base	99	743	13.32
8	Sand Subgrade	51	371	13.75
9	Silty-Clay Subgrade	43	4820	0.89

FIGURE 5.8: Percentage of out-of-control points within every material

The first column lists all the material groups that contain the anomalous values. The second column represents the number of out-of-control points within the material group, and the third column indicates the number of observations of specific material from the whole dataset.

In order to compare the number of abnormal values between the materials, I had to calculate the percentage of the out-of-control values within the material group.

The results above helped to detect that Gravel Base and Sand Subgrade material groups have a high percentage of abnormal readings. In addition, they have a significant number of observations, so we can conclude that the quality of road sensor readings depends on some features of such materials. Bituminous Aggregate and Class 5 Sp groups have a higher percentage of abnormal values than the previous ones, but to make further conclusions we need more data points.

As for the Class 6 Sp material group, besides showing an extremely high percentage of out-of-control points - more than 90%, it caused abnormal values in the results of all 3 test types which used that material. Therefore, it would be very useful to have more observations of this material type, so that to be able to make a deeper research.

The MnRoad dataset also included some weather conditions, that were during the performance of the tests. The weather attributes include average measurements of temperature, humidity, wind velocity, and precipitation of the day.

Figures 5.9, 5.10, 5.11, 5.12 show the Quality Control Charts for the MC test type, including weather data. The charts help to understand what were the weather conditions for the out-of-control points.

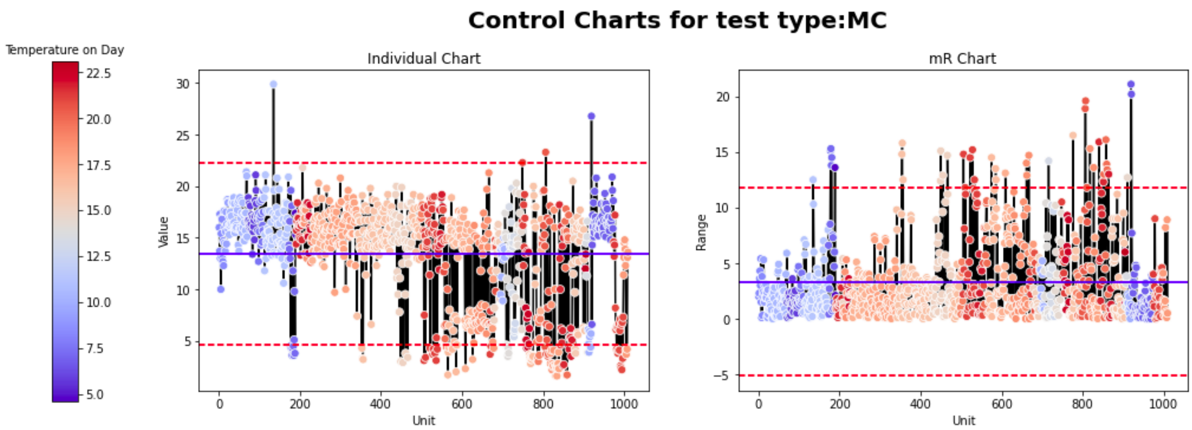

FIGURE 5.9: Quality Control Chart for MC test with temperature data

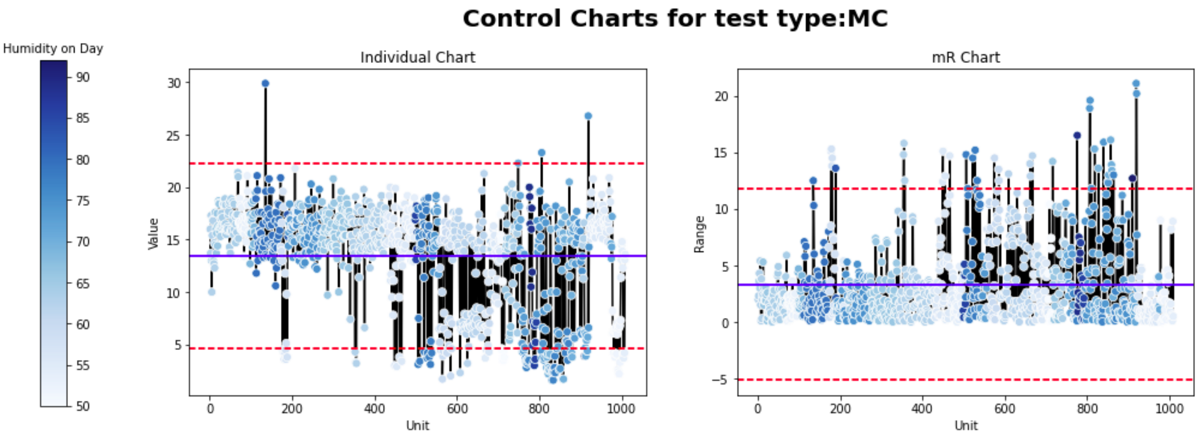

FIGURE 5.10: Quality Control Chart for MC test with humidity data

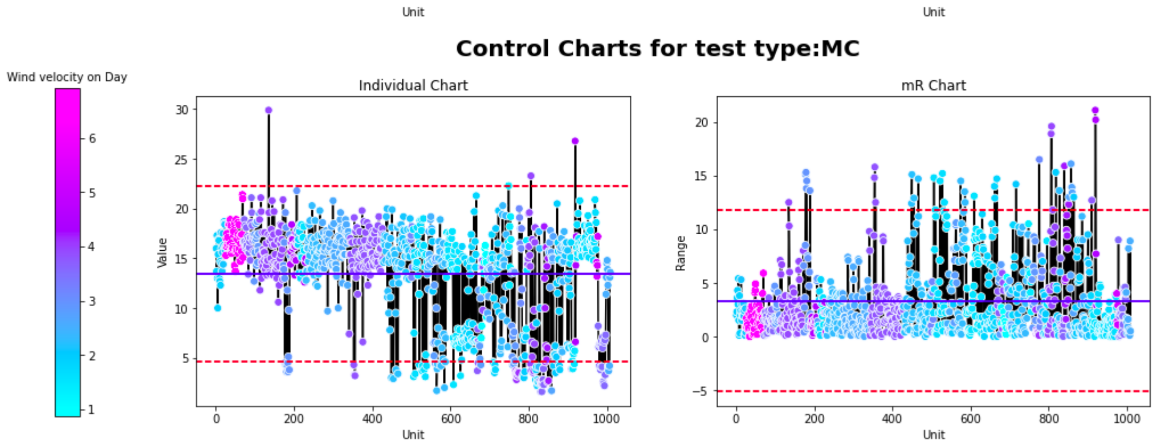

FIGURE 5.11: Quality Control Chart for MC test with wind velocity data

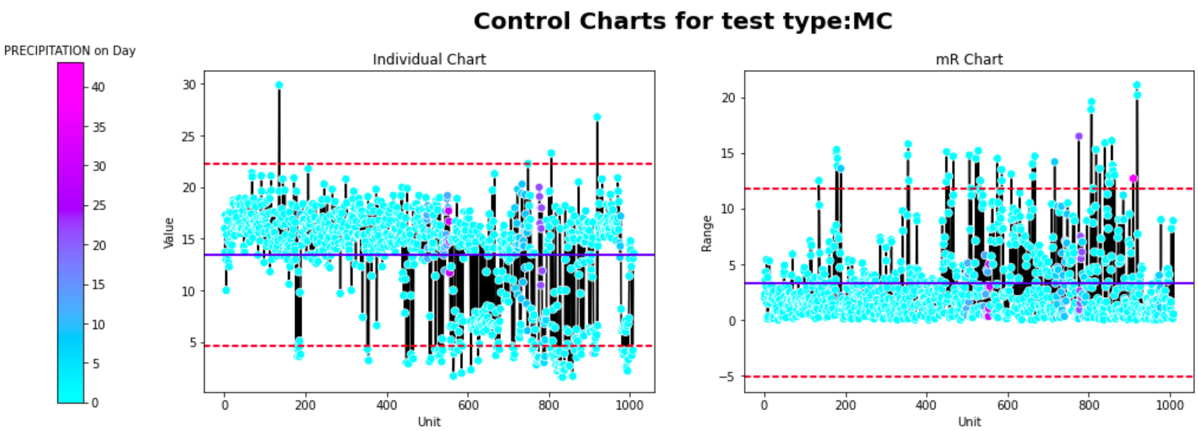

FIGURE 5.12: Quality Control Chart for MC test with precipitation data

Chapter 6

Conclusions

6.1 Results

From the developed analysis described in Chapter 5, I am certain that Quality Control Charts are an effective way to discover if a certain process (sensor readings in my case) is stable. Furthermore, in comparison to the complicated machine learning algorithms, the implementation of this approach requires only basic knowledge of statistics and a clear understanding of what type of chart to use in a specific case.

Control Charts are relatively simple to understand, provide an intuitive visualization, and are an effective solution for some initial analysis of the anomalous values.

One of the objectives of my work was also to establish the reasons for the abnormal values in the data.

It should be mentioned that with the help of control charts, I managed to discover that such material groups as: Class 6 Sp, Gravel Base, and Sand Subgrade have a high percentage of the out-of-control points (see table 5.8), thus they can be very dependent on various inferior factors and as a result, can cause unstable road sensor readings. Ideally, these would be verified with road experts; however, due to project scope constraints, I was unable to confirm these findings with road experts in Minnesota, USA.

6.2 Future work

This study could be improved and supplemented with such points:

- **More data on every test type and during all the periods of the year is needed.** As was mentioned in the Analysis section, there are almost no observations for the testing results obtained in winter. Moreover, the analysis excluded the majority of the test types because of the lack of data points; thus, we could miss some important findings from them. Therefore additional data observations would improve the analysis much.

- **Weather factors.** It would be very valuable for this research to make a deeper analysis on how the weather influence the sensor readings.

- **Get Ukrainian data.** Initially, the analysis had to be developed using the data from Ukrainian roads. The dataset included various attributes of the vehicles' characteristics. Such data could help to make research on how the vehicle types and other environmental conditions influence the sensor readings.
- **Compare the results of Quality Control Charts with the existing Machine Learning approaches.**

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