Road Test Experiments and Statistical Analysis for Real-Time Monitoring of Road Surface Conditions

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Abstract— **Road information services (RIS) is a major component of the information and communication technologies with the main purpose of RIS-based systems is to monitor road health conditions, weather information and traffic congestion. Considering the road conditions, there are various kinds of road surface types and anomalies with lack of efficient analysis of their behavior on the vehicle sensor measurements. Consequently, there are difficulties in detecting and categorizing the different road types and anomalies. This paper demonstrates road test results for the measurements of inertial sensors mounted in land vehicles while monitoring various road surface types and anomalies. In addition, a wavelet-based feature extraction together with statistical approach for the road types and anomalies are explored in this study. Two road test experiments on two different vehicles performed in Kingston, ON, Canada together with in-depth analysis are discussed in this paper.**

Keywords—Road information services; vehicular resources; intra-vehicle sensing; Road anomalies; automotive inertial sensors; statistical analysis; wavelet analysis;

I. INTRODUCTION

Recently, intelligent transportation systems (ITS) has received a significant amount of interest from the information and communication technologies (ICT) community, and at the industrial and academic level as well. According to a study provided by P&S market research in 2014, it was expected that the Global ITS market to increase from $18M to reach $38M in 2020, with a compound annual growth rate (CAGR) of 13.1% between 2015 and 2020 [1]. The evolution of computers, sensors, control, communications and electronics devices can lead to ITS solutions that save lives, time, money, energy, and the environment. Current computers and communication systems technologies are being developed in a manner to improve transportation around the world. The integration of such systems provides several forms of intelligent links between travelers, vehicles, and infrastructures to eliminate the challenges in transportation [2].

Next generation ITS systems, specifically those involved in road traffic monitoring, will be required to provide reports of traffic congestion, road conditions, and driver behavior. Road surface anomalies, as one of the road conditions indicators, contribute to increased risk of traffic accidents, reduced driver comfort and increased wear of vehicles. As a notable evidence of the anomalies effect, traffic accidents resulted from weather or road conditions are 33% of 2M+ accidents reported by Transport Canada between 2001 and 2011 [3]. Moreover, according to the American Automobile Association (AAA), two thirds of U.S drivers are worried of road surface anomalies, with approximately $3 billion a year in car repairs [4].

There are some attempts for monitoring road surface conditions but most of them were depending on 3rd party sensing infrastructure and with limitation in information variety. Furthermore, road surface conditions monitored by authorities rely on special instrumentation integrated with specific simulation software or even reported manually [5]. Some research work has addressed (RIS) and road surface anomalies. In [6] a system was developed to monitor braking events and pump detections using accelerometers, GPS and audio sensors of a smart phone. For the event localization, they relied on GSM and GPS. In addition, a system proposed in [7] used accelerometers of smart phone to classify and detect various pothole types with a GPS used for localization. RoADS, a system in [8] used smartphone's accelerometer, gyroscope and GPS sensors to classify road anomalies into three categories named severe, mild and span. Each category contained events that share similar behavior over the collected data. A back-end server in [9] was used to categorize anomalies in three categories. Data collected by vehicle mounted with accelerometer was sent to the back-end server whenever an internet-based connection is available.

Most of the available road surface monitoring systems lack full insight into the required aspects that formulate robust monitoring of anomalies. These systems presented few types of anomalies [6] or just focused in details of one type of anomalies [7]. In addition, some solutions that classify road anomalies lack adequate geo-referencing of the detected events as they rely only on GPS, which may introduce large localizing errors especially at high vehicle speed or in urban canyons [8, 10]. Generally, in urban areas and downtown cores, the localization accuracy greatly deteriorates due to GPS satellite signal blockage and multipath [11, 12].

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In this paper, we present two road experimental results held by two different types of vehicles (Van, Hatchback) and we analyze the measurement of acceleration identifying various road surface types and conditions. In addition, we provide a statistical, time domain, wavelet-based feature extraction analysis for the monitored events. The multiple monitored events are geo-referenced at 100 Hz data rate, which provides a 100 times higher system resolution over the previously proposed systems.

This paper is unique in providing an analysis of various road surface types and anomalies as monitored by low cost MEMS-based inertial sensors mounted inside two different types of land vehicles. A new approach based on wavelet analysis and statistical analysis is used to detect and identify the monitored road types. This approach enables distinguishing between different types of road surface conditions maximizing the benefits of RIS for future ITS.

In section II, we provide a discussion on the proposed road surface conditions and anomalies systems, mentioning the feature extraction techniques used. We present our system experimental setup in section III along with a discussion on the presented results. Finally, paper conclusion is presented in section IV.

II. Methodology and System Configuration

Robust road surface conditions monitoring systems should consider multiple aspects. Regarding the road surface monitoring, an appropriate data rate unit (no less than 50 Hz) should be selected, as according to anomalies structures and land vehicles average speeds the time window of the event is a fraction of second. Consequently, an adequate high data rate geo-referencing system should present as well [13].

In our proposed system, shown in Figure 1, we considered both adequate sub-systems for road types and anomalies monitoring and for accurately position the detected events. Considering the sub-system used for event detection, first, we collect linear accelerations of the land vehicle using Inertial Measurement Units mounted on the vehicle. As a second step, a wavelet-based feature extraction analysis is carried out to capture main features that distinguish multiple road surface types and anomalies. As various events introduce different frequency behavior in the linear acceleration measurements. In our wavelet analysis, we adopted the analysis approach introduced in [14-15].

Afterwards, a statistical and time domain analysis is used every 1 second time window to detect and classify the monitored event. Numerous measures and thresholds are set in this analysis as mean, ranges, variances, standard deviations, RMS, minima and maxima. In addition, time domain analysis such as zero crossing rate and thresholds crossing rates and number of peaks at each time window.

For geo-referencing, once an event is monitored by the first sub-system, a high data rate of position is calculated and labelled the detected event. Finally, a record of an event is used to update a created dataset includes the event classification descriptive statistics and an adequate position.

III. Experimental Analysis

A. Experimental Setup

To validate and explore the capabilities of our proposed system, an Experimental setup shown in figures 2 and 3 has been prepared for two outdoor trajectories. The first trajectory utilized a Chevrolet long land vehicle while second trajectory held using Pontiac vibe, a hatchback land vehicle. Both vehicles carried the MEMS grade Crossbow inertial sensors, Novatel OEM4 GPS receiver and MiVue 388 Dash Cam. The Crossbow inertial measurement unit was used for measuring accelerations of both vehicles during the trajectory at 100 Hz of data rate. While, the Novatel OEM4 GPS receiver was used to provide geo-referencing. The MiVue 388 Dash Cam used to record the two trajectories. The videos recorded of the two trajectories was used to build a database including types of road anomalies and their corresponding occurrence time used as a reference.

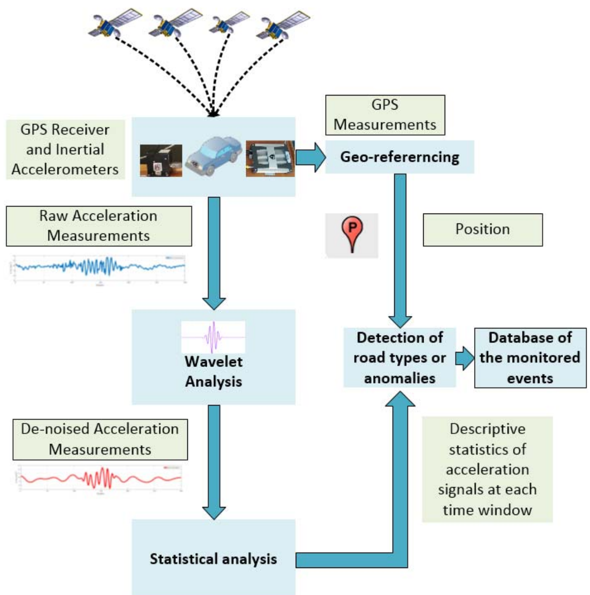

Figure 1. Proposed system used for monitoring road surface types and anomalies.

Figure 2. Cameras attached to the land vehicle (Hatchback) windshield for second trajectory recording.

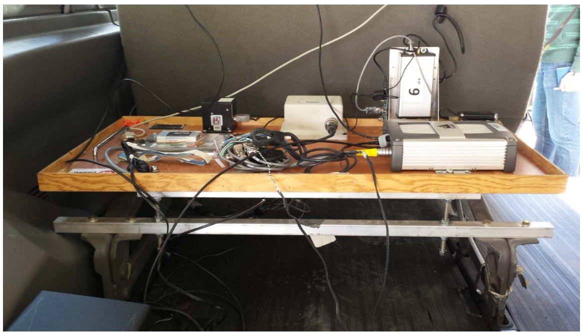

Figure 3. Testbed used for mounting the sensors on the two vehicles used for the two trajectories.

B. Results and Disscussion

The experimental setup explained in section III.A is used for two trajectory experiments. Both trajectories were held in Kingston, ON, Canada. The two trajectories, shown in figures 4 and 5, lasted for almost 40 minutes each including high traffic time, traffic light stops and stationary times.

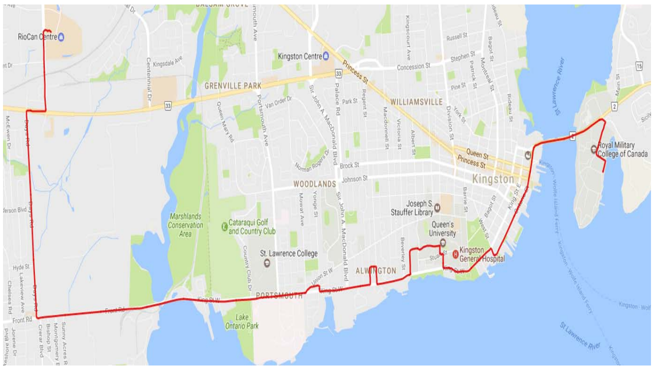

Figure 4. First experiment trajectory in Kingston, On Canada using a long land vehicle (**Van**).

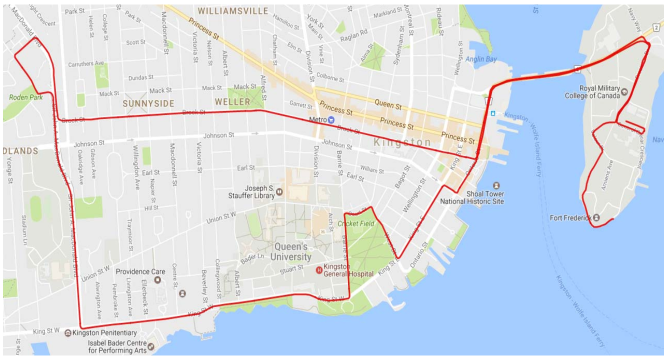

Figure 5. Second experiment trajectory in Kingston, On, Canada using a land vehicle (**hatchback**)

The two trajectories experienced various types of road surfaces and anomalies. Some of these types and events can be classified under same category as they have high similarities on their behavior through the collected acceleration data. To present a deep insight over these events, various figures for the accelerometers data during driving over multiple road types and anomalies are presented. In the provided figures, the vertical acceleration is in +ve direction of Z-axis, transversal acceleration is in the +ve direction of X-axis and the forward directions is in the +ve direction of Y-axes. Figure 6 shows the accelerometers readings through a time window of three seconds for an almost road driving condition. On the other hand, some road types can be wrongly detected as a road anomaly. Figures 7-10 shows the vehicle drive through a time window of 3 seconds for two different road anomalies and two road types. As illustrated in the figures, driving over long time of fatigue (crocodile) cracks or longitudinal cracks have a close behavior in the acceleration data to the ones of paver road and steel causeway driving.

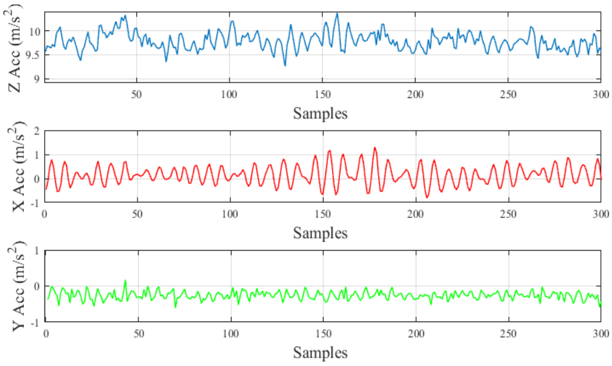

Figure 6 Vehicle acceleration levels during (**smooth**) road driving.

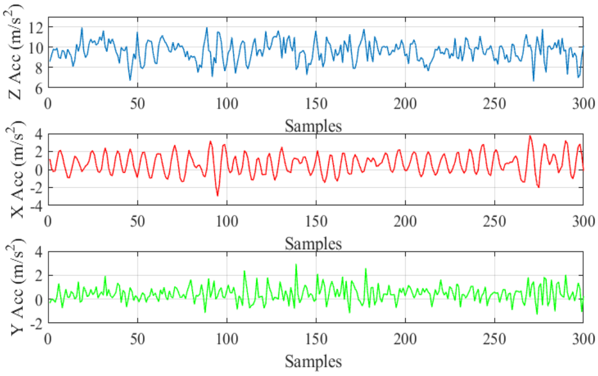

Figure 7. Vehicle acceleration levels during (**fatigue (crocodile) cracks**) road driving.

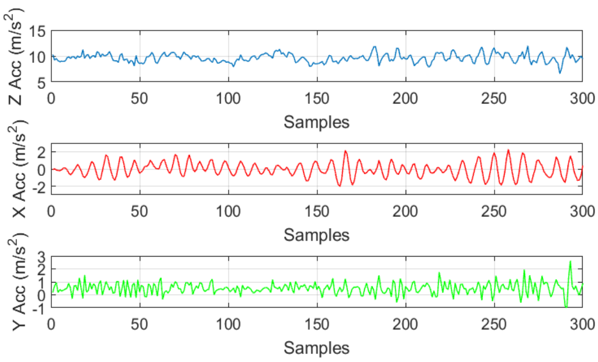

Figure 8. Vehicle acceleration levels during driving over (**longitudinal cracks**).

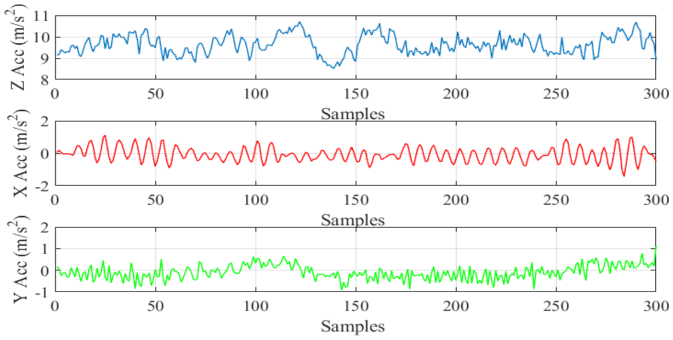

Figure 9. Vehicle acceleration levels during (**paver**) road driving

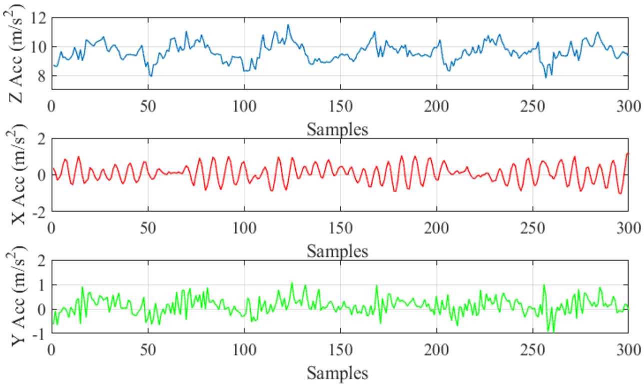

Figure 10. Vehicle acceleration levels during (**steel causeway**) driving.

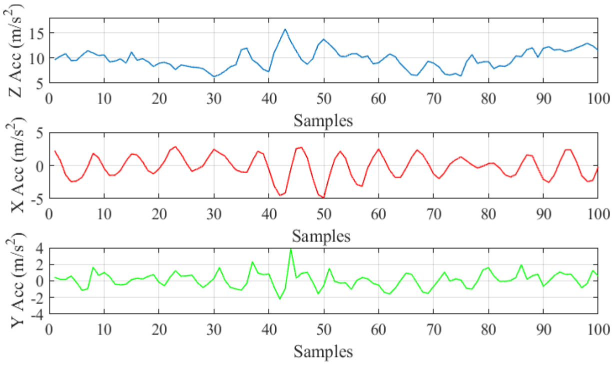

Figure 11. Vehicle acceleration levels during driving over a (**pothole**).

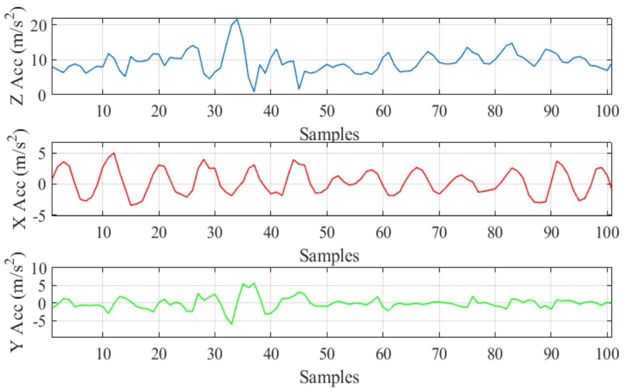

Figure 12. Vehicle acceleration levels during driving over a (**manhole**).

Figures 11 and 12 show the similarity in the effects of the driving over potholes and manholes on the acceleration data. Further, figures 13 and 14 indicate also alike behavior of driving over a transverse crack and bridge expansion joint. Finally, figure 15 clarifies the effects of driving over a railroad crossing. Figures 6-15 are all extracted of the trajectory held using a long land vehicle (Van). The purpose of that is the challenges of sensing a road type or anomaly while driving a long land vehicle due its weight and large wheels.

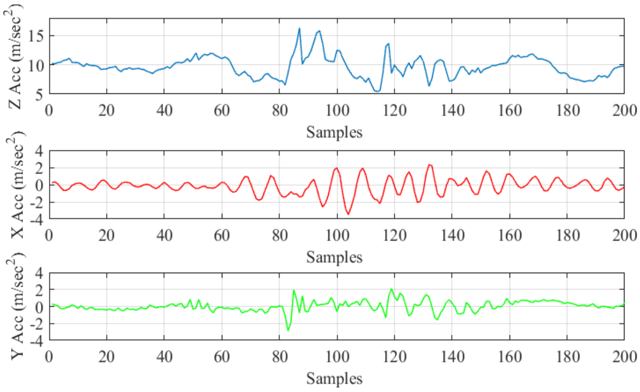

Figure 13. Vehicle acceleration levels during driving over (**transverse-cracks**).

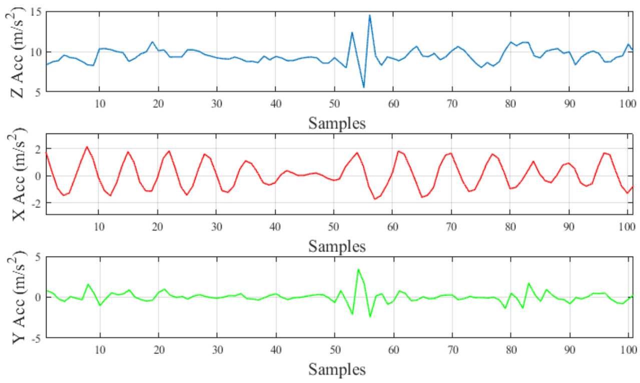

Figure 14. Vehicle acceleration levels during driving over (**bridge expansion joint**).

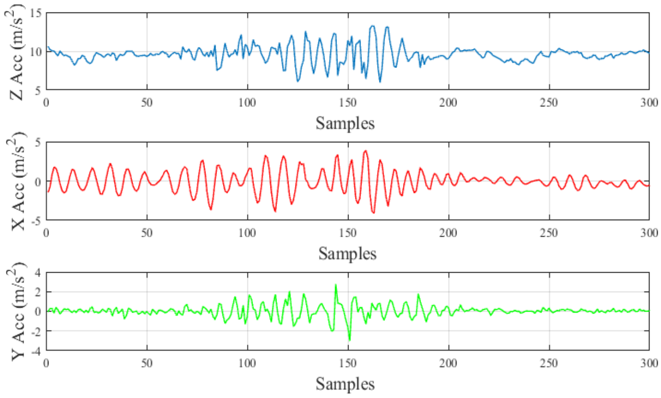

Figure 15. Vehicle acceleration levels during (**railroad crossing**) driving.

To demonstrate the advantage of using wavelet analysis in extracting features of specific road type and distinguish it from road anomalies, figure 16 shows the Z acceleration levels during a window of 3 seconds before (a) and after (b) wavelet analysis. During the second number 2 the vehicle crossed a railroad, which has features can be common with any other cracks. The wavelet analysis were able to keep its main features while smoothing the data in first and third second.

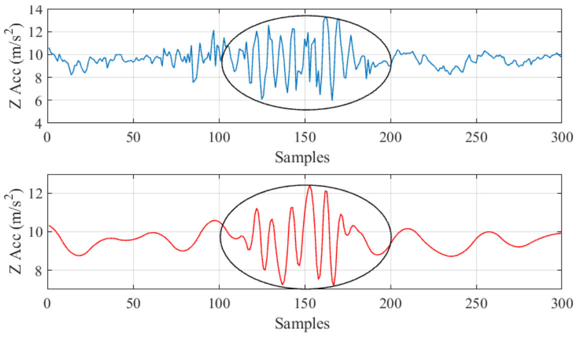

Figure 16. Vehicle vertical acceleration during (**railroad crossing**). a) Before analysis b) After wavelet analysis.

To assess the capabilities of our proposed system, we highlight results of road types and anomalies detection during common roads driven through both trajectories. Figure 17 shows the assessed common roads of both trajectories. For the long land vehicle, in the first common portion, there were 3 major anomalies present, which are 11 manholes and 1 severe pothole and 8 transverse cracks located between portions of smooth driving. Table 1. Summarizes the detected numbers of anomalies, it is worth mentioning that the only present pothole was a sharp one and was wrongly -detected as a manhole. Regarding transverse cracks, 1 was mis-detected and 1 smooth driving were detected as a crack. Figure 18 shows the detected manholes (red) and transverse cracks (green).

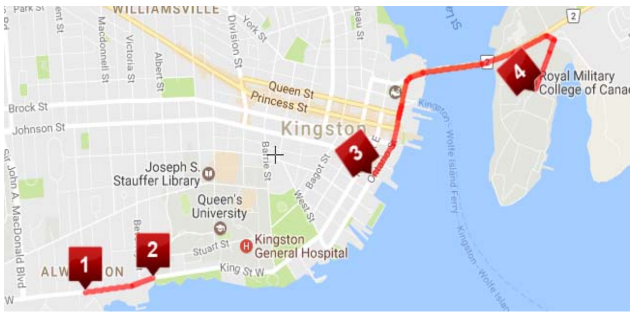

Figure 17. Monitored parts of the two trajectories

Table. 1 Types of anomalies in first monitored part of the first trajectory

Anomaly Type	Number of Attended anomalies	True Positive	False Positive	False Negative
Manholes	11	9	2	2
Pothole	1	0	1	1
Transverse Cracks	8	7	1	1

For the hatchback land vehicle, during the first common portion, the land vehicle attended 12 manholes, 2 potholes, and 9 transverse cracks as shown in table 2. Figure 19 shows the detected events, manholes (red), potholes (blue), and transverse cracks (green). Results show that the hatchback land vehicle is more sensitive to the anomalies than the long land vehicle due its less weight and tires size. With regard to the second common part of the two trajectories, the first trajectory utilized the long van has attended 35 events which are 10 manholes, 7 potholes, 14 transverse cracks and 4 bridge expansion joint. Table 3 and figure 20 show the detected manholes (red), potholes (blue), cracks (green) and joints (white). Table 4 and figure 21 summarize the detected events for the common second portion utilizing the hatchback vehicle. Similar to the first portion, analysis of the second portion shows that the hatchback land vehicle is more efficient in detecting road types and anomalies.

Figure 18. Monitored road anomalies in the first common portion detected in (**long land vehicle**) trajectory.

Table. 2 Types of anomalies in first monitored part of the second trajectory

Anomaly Type	Number of Attended anomalies	True Positive	False Positive	False Negative
Manholes	12	11	1	1
Pothole	2	1	1	0
Transverse Cracks	9	8	1	1

Figure 19. Monitored road anomalies in the first common portion detected in (**hatchback land vehicle**) trajectory.

IV. Conclusion

This paper demonstrated an analysis of various types of road surface types and anomalies as monitored by low cost MEMS-based inertial sensors mounted inside two different types of land vehicles. We also suggested a method based on wavelet analysis and statistical approach to detect and identify the monitored road types. In addition, we observed the different impact by the anomalies as monitored by the sensors at different vehicle types. Our analysis could distinguish between different types of road surface conditions maximizing the benefits of RIS for future ITS.

Table 3. Types of anomalies in second monitored part of the first trajectory

Anomaly Type	Number of Attended anomalies	True Positive	False Positive	False Negative
Manholes	10	8	2	2
Pothole	7	5	2	2
Transverse Cracks	14	10	1	4
Bridge expansion joints	4	3	1	1

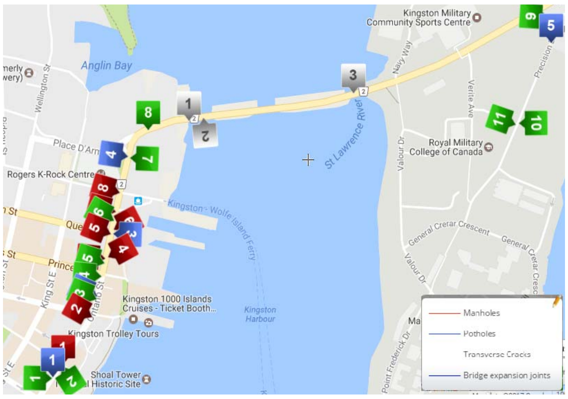

Figure 20. Monitored road anomalies in the second common portion detected in (**long land vehicle**) trajectory.

Table 4. Types of anomalies in second monitored part of the second trajectory

Anomaly Type	Number of Attended anomalies	True Positive	False Positive	False Negative
Manholes	10	9	1	1
Pothole	8	6	2	2
Transverse Cracks	14	11	1	3
Bridge expansion joints	4	4	1	0

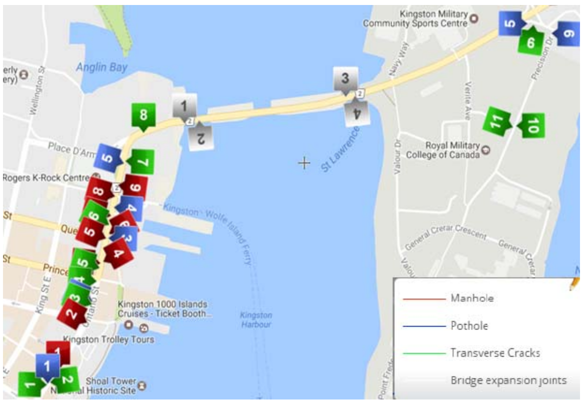

Figure 21. Monitored road anomalies in the second common portion detected in (**hatchback land vehicle**) trajectory.

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