Measuring the Acceleration of the Montreal Metro using an Arduino Train Accelerometer

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INTRODUCTION

Our goal is to collect data on the acceleration experienced in the Montreal metro. We use an Arduino electronic circuit to power an accelerometer within a box we place on the metro for this purpose. We look at vibration levels, maximal acceleration, and maximal deceleration as comparisons between different lines and train types.

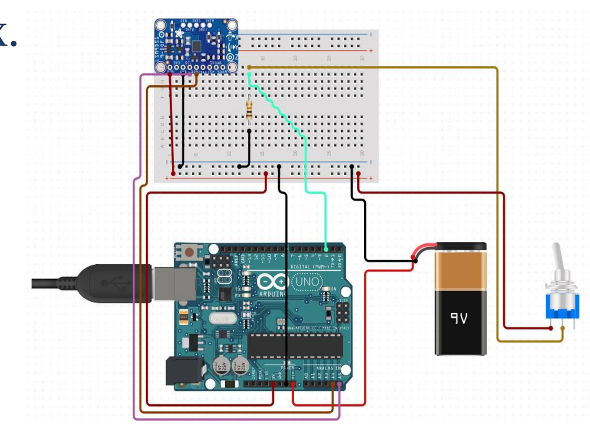
The questions answered by this project are ones that we naturally asked ourselves when taking the metro every day getting to school. We use the framework of the Dawson College MakerSPACE initiative to demonstrate the feasibility of testing our hypotheses using an easily available electronic sensor kit.

Objectives: The collected data allow us to compare the different lines (Green, Orange, Yellow, Blue) and train models (MR-73, MPM-10 “Azur”) that operate in the metro. Individual sections of the rail network are also analyzed separately to track changes over the same line. Each axis of acceleration (frontal, lateral, vertical) can be quantitatively analyzed to obtain different information.

Analysis: We use the variance on the lateral and vertical axes as a measure of vibrations. The extrema of frontal acceleration are verified against theoretical data. Lateral acceleration is compared qualitatively against a map of the metro network to evaluate the precision of the hardware for further research focused on sensing curves and turns.

DESIGN

Our setup, housed within a cardboard box, comprises an Arduino microcontroller interfaced with an accelerometer. Friction strips on the bottom of the box stop it from sliding. The circuit is powered by a 9V battery and controlled by a switch accessible from outside the box.



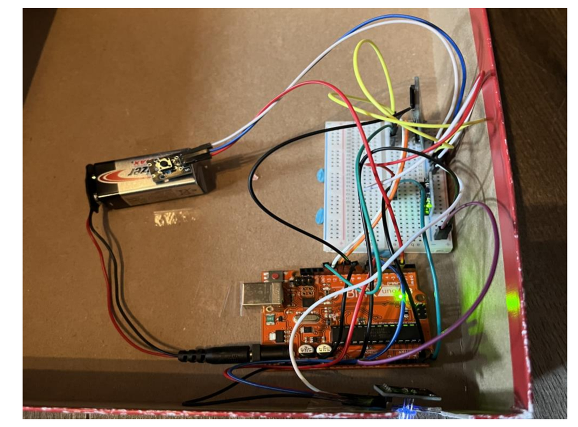


Fig. 1: Electric circuit diagram and experimental setup

During the experiment, the Arduino circuit records acceleration data at regular intervals. Each data point includes measurements of acceleration along the three axes.

```
if (isCollecting) {
  // make a string for assembling the data to log:
  prevState = true;
  String dataString = "";
  /* Get new sensor events with the readings */
  sensors_event_t a, g, temp;
  mpu.getEvent(&a, &g, &temp);
```

```
//Write data to SD
dataString += String(a.acceleration.x - calX);
dataString += ",";
dataString += String(a.acceleration.y - calY);
dataString += ",";
dataString += String(a.acceleration.z - calZ);
dataString += ",";
```

Fig. 2: Examples of the code for the Arduino circuit

Data collection method: The device is powered before entering the metro, then placed on the floor of the metro. The orientation is always the same relative to the train. Before the train leaves, the switch is used to start the data collection. After this point, the device should not be touched to avoid interfering with the sensor. At the end of the line, once the metro is fully stopped for at least two seconds, the switch can be deactivated, and the box picked up.

DATA ANALYSIS

In total, 20 runs were done in the four lines of the metro, totaling 200 interstations (95 green, 74 orange, 10 yellow, 21 blue; 128 Azur, 72 MR-73).

Theoretical data for the forwards acceleration and deceleration is provided by the STM for its Azur trains, but not for the MR-73[2]. Data was found for the older trains[3], but its reliability is not established as a primary source was not found.

	Acceleration (m/s^2)	Deceleration ($-m/s^2$)
Azur	1.207	1.790
MR-73	1.43	No data

Fig. 3: Theoretical maximum acceleration and deceleration.

1. Calibration

Data collected from the accelerometer has an offset at rest from the expected 0 m/s^2. We add the required offset to all datapoints from a run to make the total average acceleration of the run equal to 0. The average value of the acceleration on the whole run is equal to the change in speed, its derivative, during the whole run. Our protocol specifies the sensor must begin and end at rest, so the average value must be 0.

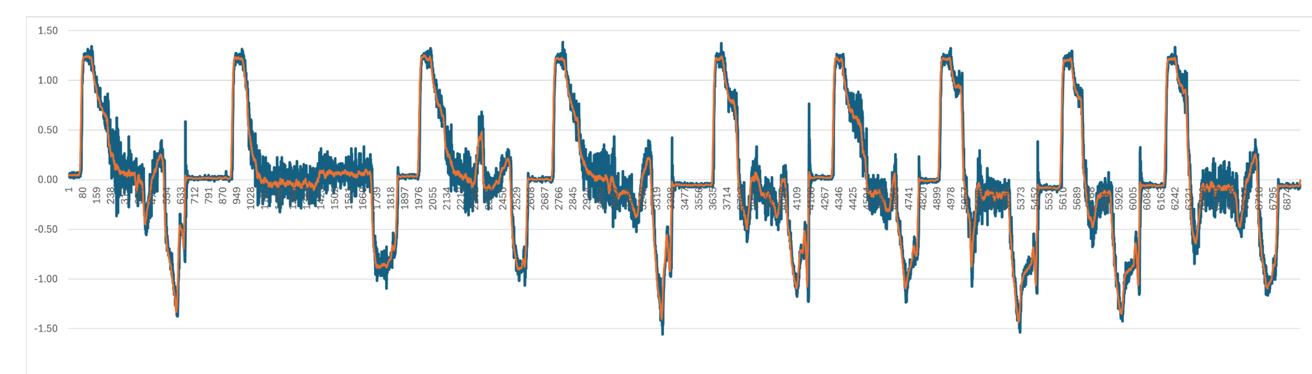


Fig 4. Example graph of frontal acceleration over time (orange line, from Sauvé to Berri-UQAM). In blue: raw data; in orange: 10-point average.

2. Maximum acceleration and deceleration

The average of the frontal acceleration over 10 datapoints is taken for the entire run, minimizing the noise in the data. For each interstation (period during which the train is traveling from one station to the next), the highest and lowest values are recorded. They are respectively plotted in Figures 3 and 4.

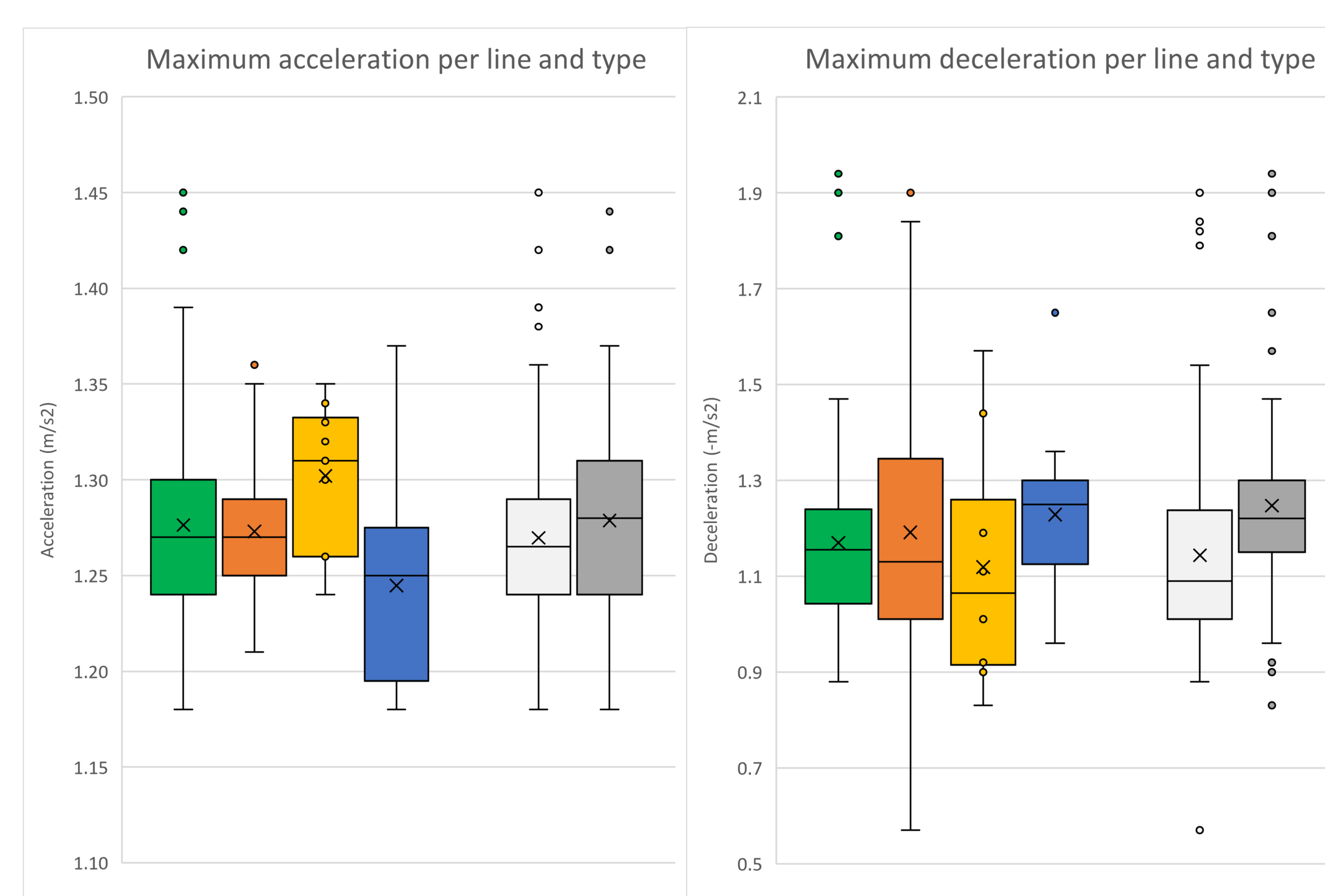


Fig. 5 and 6. Box plots (whiskers show 1.5 IQR) for the maximum acceleration (left) and deceleration (right) for each interstation of the metro. The median is indicated by a horizontal line, the average by a cross. All datapoints are part of one of the first four categories and one of the last two. Outliers are shown for all categories, all points for the Yellow line are shown because of the small sample size (n=10)

3. Vibration levels

The standard deviation of the lateral and vertical accelerations is chosen to measure vibrations because as a train vibrates, the accelerometer will record rapidly changing values. The standard deviation is taken for a moving interval of 100 points, then smoothed by a moving average of 255 points. The highest value this function reaches during each interstation is defined as the “vibration level” of that section and recorded as one datapoint.

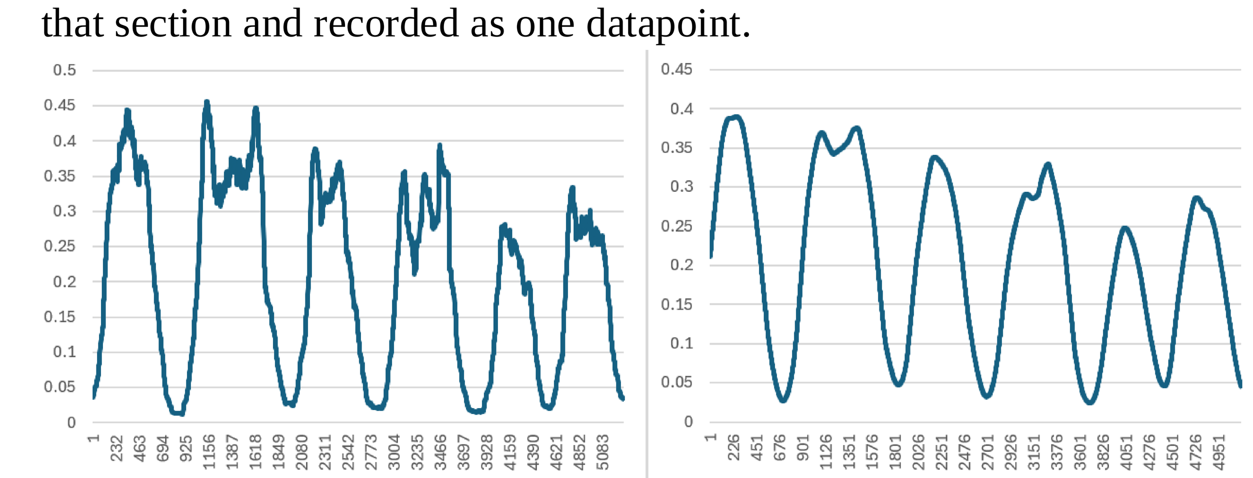


Fig 7. (Left) Standard deviation over 100 points for a portion of the orange line. (Right) Average over 255 points of the first graph.

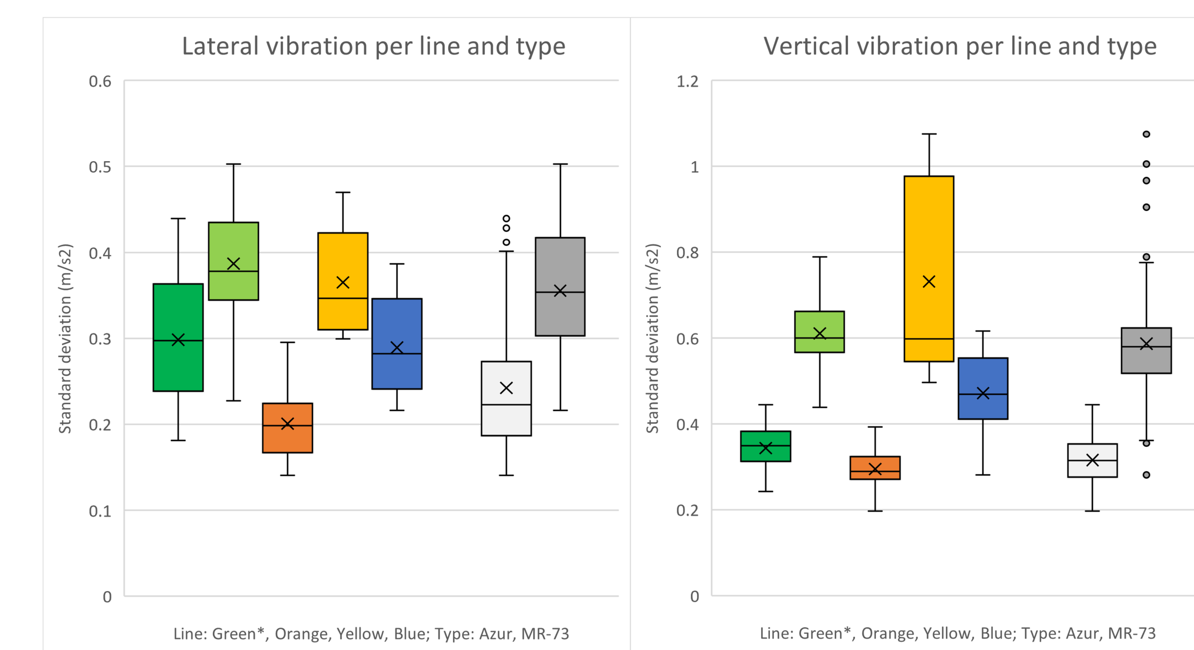


Fig 8 and 9. Box plots (whiskers show 1.5 IQR) for lateral and vertical vibration level for each interstation. Parameters are the same as for fig. 3 and 4.

4. Lateral acceleration on the metro map

Lateral acceleration can be used to detect when the metro is turning due to the radial acceleration necessary in any curve, but also because tracks are often tilted towards the center of curvature. Both phenomena are sensed by the accelerometer in the lateral axis. Our research does not use this quantitatively, but we include an example of qualitative comparison as a proof of concept for future research.

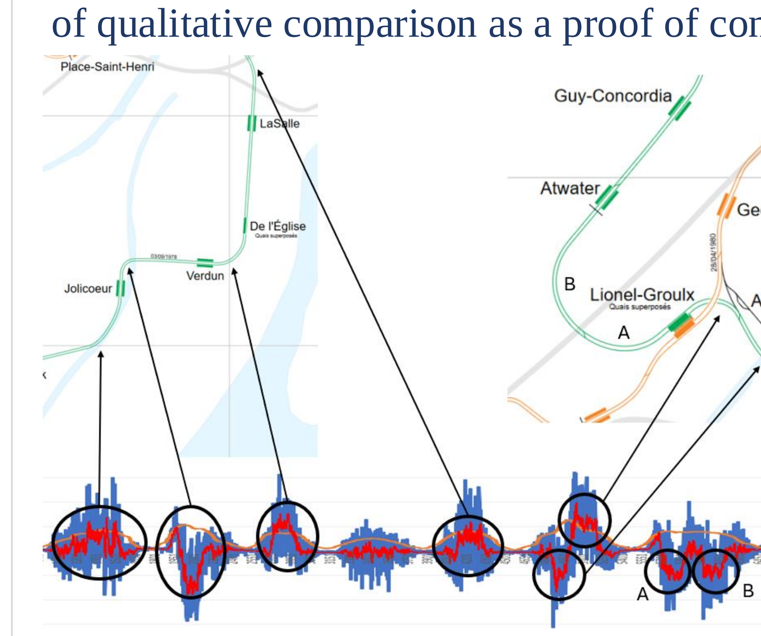


Fig 10. Comparison between lateral acceleration from stations Monk to Lionel-Groulx, and the map of this section of the track. Curves can be seen reflected in the peaks of the acceleration graph.

Map from “Plan du Métro et REM,” by Franklin JARRIER. With permission from the author. https://cartometro.com/metro-montreal/

RESULTS

Acceleration and deceleration

- The yellow line has the highest acceleration (average 1.30 ± 0.04), while the blue has the lowest (1.24 ± 0.05). The green (1.28 ± 0.06) and orange (1.27 ± 0.03) lines are almost equal.
- The blue line has the highest deceleration (-1.23 ± 0.15), while the yellow has the lowest (-1.07 ± 0.24).
- The Azur and MR-73 train types have similar acceleration values (1.27 ± 0.04, 1.28 ± 0.05), but the Azur is more consistent (lower SD.)
- The MR-73 (1.25 ± 0.19) has a higher deceleration than the Azur (1.14 ± 0.22).

Vibrations: The MR-73 and lines that use it have a higher level of vibrations than the Azur, with the yellow line being the highest and the orange line the lowest. The vertical vibration level is much more distinct than the lateral between Azur and MR-73.

Theoretical data: Almost all Azur datapoints go beyond the expected maximum values for acceleration and some for deceleration, while the limit for MR-73 seems to match.

Lateral acceleration: Qualitative interpretation is possible by comparison to a reference map.

CONCLUSIONS

From the data analysis, it is clear that there are quantifiable differences between the different lines and trains. For maximum acceleration, the yellow line has the highest values and the blue line has the lowest. As for maximum deceleration, it is the inverse. For vibrations, the MR-73 has a distinctly higher levels as compared to the Azur train. It is also possible to detect curves from the lateral acceleration data. Finally, our experimental values mostly exceed the theoretical values.

Limitations

The metro does not travel on flat ground in the tunnels, thus components of gravity are registered as frontal acceleration. This can explain values higher than their theoretical maximum.

Our dataset is potentially not representative of the entire metro network. The number of downtown stations and runs during rush hour is higher, for example, due to our process of collection.

Further research

Using an Arduino-compatible gyroscope would allow determination of the angular orientation of the metro at any time, thus correcting the erroneous acceleration. Once this is accomplished, we will be able to analyze the REM also.

Numerical integration of the frontal acceleration could make calculating the speed reached by the metro possible, giving more data to compare to theoretical values.

With more data, we would be able to compare the acceleration and vibration differences between older and newer tracks.

ACKNOWLEDGEMENTS

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The Arduino code was adapted from code by Adafruit and Tom Igoe.

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[1] T. K, “Accelerometer Basics - learn.sparkfun.com,” *Sparkfun.com*, 2019. https://learn.sparkfun.com/tutorials/accelerometer-basics/all

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