Development of an Accelerometer Based Wheel-Flat Detection System for a Subway Transit System in Toronto

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ABSTRACT

An accelerometer based wheel condition monitoring system for the subway transit system in Toronto was developed utilizing vibration signals and signal processing techniques. Signal analysis techniques including cepstrum analysis and the discrete wavelet transform were employed for the detection of the wheel-flats. An in-service measurement was conducted on a subway line and the results were compared against an existing force sensor based wheel-flat detection system.

It was concluded that this proposed accelerometer based system is able to identify specific wheels with large flats and quantify the length of wheel flat. In addition, further measurements and analysis were recommended to confirm any reduction in surface vibration as a result of being able to identify trains with large wheel flats during service and re-direct them to the yards for maintenance. Further study was also recommended in terms of determining acceptable levels to keep the subway system in a state of good repair moving forward.
INTRODUCTION

In densely populated urban areas such as the city of Toronto in Canada, underground railways are an important solution for traffic congestion. However, subway trains generate vibrations which propagate from the wheel-rail interface in the tunnel through the surrounding soil, and interact with the foundations of nearby buildings.

It has been known that one major source of railway noise and vibration is impacts generated by wheel-flats on train wheels [1, 2]. These impacts may cause severe damage to the wheel-set and track components. To prevent severe impact vibration and further damages on the wheel-rail parts, the identification of specific trains with large wheel flats has been required.

Methods used for wheel condition monitoring can be categorized by the signal types measured by the system: direct measurement of dynamic load using force sensors and vibration measurement of the rail with accelerometers [3]. The applied load due to wheel-flats can be directly measured by strain gauge, fiber-optic cable, or force sensors. The main advantage of measuring the force directly is that the exact load applied to the rail structure is known based on the relationship between the applied load and the deflection of the structure. Also, it is known that the applied load is associated with the damage on the wheel. However, since the linear excitation occurs only in certain region near the sensors, the force between the wheel and rail cannot be monitored for the entire circumference of the wheel with single sensor [3]. On the other hand, the accelerometer based system determines the applied load to the rail by measuring the dynamic motion of the rail, and then the wheel condition is calculated by processing the data. The main advantage of this method is its ability to monitor the entire circumference of the wheel with single sensor [3]. This method, however, require more processing power than other type of system. Since accelerometer based systems are simple and cost effective compared to other types of systems, this study was focused on the development of an accelerometer based wheel-flat detection system.

Bracciali and Cascini [4] showed the possibilities of the cepstrum analysis to detect the existence of periodic impacts on the rail due to the wheel-flats. However, the vibration signal associated with a wheel or bogie from the signal of a train pass-by had to be selected manually for the cepstrum analysis. Belotti et al. [5] employed the wavelet transform to create bogie-mask windows which were used to select a set of vibration signals associated with each bogie from the measured data for each train pass-by. However, this method cannot show the existence of periodic impact typically associated with wheel-flats.

In this study, the performance of an accelerometer based wheel-flat detection system was demonstrated. Both cepstrum analysis and wavelet transform techniques were employed to identify the existence of a wheel-flat and to generate bogie-mask windows. The developed system was installed for the vibration measurement on rail structure which was conducted in October of 2012 in Toronto. The results obtained from the accelerometer based system were used to evaluate the thresholds of the existing force
based wheel-flat detection system. It was expected that the results obtained from this
 test provided better understanding how the existing wheel-flat system, which was
 utilizing fibre-optic technology to measure force signals, was categorizing wheel-flats.

MEASUREMENT SETUP

The wheel-flat measurement was conducted during the morning rush-hour period
totalling six (6) hours. Three (3) accelerometers were used for measuring vibrations
directly on the rail and one (1) accelerometer was mounted directly on the invert, which
is the base of the concrete subway tunnel, next to the rail sensor as shown in Figure 1.
Channels 1 and 2 were mounted on the base of the rail mid-span between the rail pads.
Channel 3 was mounted on invert next to the west-bound north rail. The optical sensor
channel was mounted approximately 50 ft ahead of Channels 1, 2 and 3.

The measurement was conducted at the same location where the existing forced based
wheel-flat detection system was installed under the rail. This system was installed on
the section of double-tie type track bed.

One benefit of the discrete wavelet analysis is the ability to calculate the train speed
without an additional magnetic or optical sensor. The train speed can be calculated with
this signal processing technique directly from the sensor located on the invert. The
optical sensor is used to verify the train speed calculation. All signals were acquired
directly in a digital form using the LMS® data acquisition and signal analyzer. The
system was triggered by the optical signal when a subway train passed by the area.

Figure 1: Measurement Layout (WB Rail)
ANALYSIS PROCEDURE

This accelerometer-based wheel condition detection method requires three (3) accelerometers to measure the motion of each rail (Ch1 and Ch2) and invert (Ch3). Since frequency-domain analysis does not provide sufficient information for adequate wheel-flat detection, the results of the analysis for this application are presented in the time-domain.

For each train pass-by, the train speed was calculated based on the vibration data obtained from the invert channel (Ch3) through the Discrete Wavelet Transform (DWT). Each axle of every subway car was detected and used to calculate a speed. The speed for each train was then reported based on the average speed of all 24 axles (6 subway cars, 4 axles per car). Utilizing this method for speed calculation and axle detection, an additional optical sensor for speed calculation or axle counting may be redundant. This train speed was then compared with the speed calculated from the optical sensor data as a part of a validation process. The train vibration signal was then split up into sections representing a single rotation of a wheel centred along each axle known as the axle-mask windows. These axle masks windows are then applied to the rail vibration signal (Ch 1 and 2) now representing each wheel of the subway train and are used for further analysis.

On the other hand, vibration data from the rail channels were used to calculate wheel-flat and wheel condition coefficients for each wheel. Calculated parameters for each wheel of the train include coefficients representing wheel condition, peak acceleration levels and signal energy. In addition, the existence of periodic impacts, which could be provide further information of each wheel are examined via the cepstrum analysis.

The details of wheel-flat detection and analysis procedures are described in the following subsections.

DWT for Creation of Axle-mask Windows and Train Speed

The most important process in this wheel-flat detection system was creation of axle-mask windows for each train pass-by. The axle-masks windows are critical for determining which subset of the rail vibration data corresponds to a given axle. Since this process is used for detecting imperfections on the wheel, it is crucial that the correct wheel is tagged for defects if it is to be sent the maintenance yard for repair. It should be noted that the axles are separated in a bogie by approximately 6.6ft for the subway train while the wheel circumference ranges between 6.6ft and 7.2ft. So it is possible that two adjacent axle-mask windows in a bogie could be superimposed. This superimposing problem may reduce the accuracy of which axle within the bogie has the defect. From a practical viewpoint, however, this is not a significant problem: if a wheel of a car is damaged, the car shall be detached from the train and the bogie with the damaged wheel will be tagged and sent to the maintenance yard for service.

Wavelet Transform
The continuous wavelet transform (CWT) uses inner products to measure the similarity between a signal and an analyzing function which is a wavelet, $\psi$, and can be expressed as [6]:

$$C(a, b; f(t), \psi(t)) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi^* \left( \frac{t-b}{a} \right) dt,$$

(1)

where $a$, $a > 0$, is the scale parameter, $b$ is position parameter, and $*$ denotes the complex conjugate of mother wavelet, $\psi$.

If the scale and position parameters are selected based on power of two (dyadic scales and positions), the process will be more efficient but will maintain accuracy. This analysis can be obtained from the discrete wavelet transform (DWT), and where the scale and position parameter should be expressed as:

$$a = 2^m \text{ (dyadic scale)}; b = na \text{ (dyadic shift)},$$

with $n, m \in N$, where $m$ is called the wavelet level.

**Axle-mask Windows and Train Speed**

For the generation of the axle-mask windows, the DWT technique was applied as Belotti et al. [5] proposed. A proper selection of the mother wavelet allowed counting the axles of each train pass-by possible [6].

Utilizing the wavelet transform, an additional optical signal or other measure such as magnetic axle-counter block, which is installed as part of the existing force based wheel-flat detecting system, is not required to count axle passbys or to calculate train speed. In this method, the DWT of the vibration data from invert (Ch 3) was used to create the axle-mask windows and to calculate train speeds.

The dynamic load due to the axle passing on rail has been known to have frequency content lower than 50 Hz [2]; hence, at the present sampling frequency of 10,240 Hz, it was found that examination of higher level information from DWT was the most suitable for this application. The DWT to the acceleration signal from the invert generated by a train pass-by is shown in Figure 2. The axles pass through the accelerometer on the invert are clearly identified as depicted in the figure.

Once the condition detection system had determined the position of each axle of the train in the time domain, the speed for each train was then reported based on the average speed of all 24 axles. The axle-mask windows were determined taking into account the calculated speed of the train. For the peak acceleration of each wheel, the window size represents a single rotation of wheel, while three (3) rotations of wheel for the cepstrum analysis.
Figure 2: Discrete Wavelet Transform of Vibration Signal from Invert Peak Acceleration and Energy

Since the response of the rail from an impulse vibration is a function of wheel-flat height [7], the peak acceleration levels of the rail within a single wheel rotation were reported for each wheel. The acceleration was reported in units of gravity (“g”).

In addition, the signal energy level of each data segment representing approximately 1/2 rotation of wheel was estimated for the N samples of data with zero average [4]:

$$\sigma^2 = \frac{\sum_{i=1}^{N} s_i^2}{N-1}$$  \hspace{1cm} (2)

where $s_i = s(i \Delta t)$ with $i = 1, 2, ..., N$. Then, the estimated energy level was then integrated for each axle.

Potential Existence of a Wheel-Flat via cepstrum analysis

The existence of a wheel-flat typically involves periodic impacts generated on the rail and has a specific association with periodicity which is based on the train speed and
wheel diameter. The cepstrum analysis was carried out to determine the existence of echoes in the recorded signal which would represent repeated impacts of similar nature. The cepstrum analysis was proposed as a better alternative to the autocorrelation function for the detection of echoes in seismic signals. The definition of the cepstrum analysis is the inversion Fourier transform of the logarithmic power spectrum [8]:

$$ C_{AA} = \mathcal{F}^{-1}\{\log S_{AA}(f)\}, $$

where $S_{AA}(f)$ denotes the power spectrum of a time signal $a(t)$.

A problem however does exist as the wheel diameters are not all consistent and can vary by as much as 3 in. As a result, a single revolution of a wheel could vary between 6.6ft and 7.3ft, which introduce a slight variation in the wheel-flat signal depending on the wheel diameter. The algorithm used in the detection system attempted to take into account the varying wheel diameters when identifying a potential wheel-flat.

A wheel was flagged with a potential wheel-flat if the system had detected a repetitive nature of the signal (based on cepstrum analysis) and the peak rail acceleration levels were 80g or higher. The physical position of the accelerometer on the rail can have an effect on the measured peak rail accelerations depending on where the wheel-flat contacts the rail relative to the sensor position. During this measurement campaign, an additional 4 sensors were placed away from Channels 1 and 2 in order to try and capture this difference. As such the criteria for peak accelerations above 80g was applied on all channels, however, the values reported in this paper correspond to those measured on Channels 1 and 2.

**Wheel-flat Length Estimation**

When the system detected the potential existence of a wheel-flat, the estimated wheel-flat length was calculated and reported. In general, if the train reaches a critical speed then the force generated on the rail from a wheel-flat is consistent regardless of further increasing past the critical speed [7]. The critical train speed depends on the material properties of the rail and wheel, as well as the car mass supported on each wheel. The determination of the wheel-flat size depends on whether or not the critical train speed is exceeded.

The critical speed for the elastically supported rail can be written as [7]:

$$ v_c \cong v_r \left[1 + \left(\frac{m}{M}\right) \frac{\beta}{2}\right]^{1/2} \text{ with } v_r = \left[g a (1 + \frac{M}{m})^{1/2} \right], $$

where $g$ is gravitational acceleration, $M$ is the portion of the sprung mass of a wheel, $m$ is the wheel mass, $a$ is the radius of the wheel $\rho_1$ is the mass per unit length of rail and $\beta = \left[\frac{K}{4E I}\right]^{1/4}$ (where $K$ is foundation stiffness per unit length of rail, $E$ is Young’s modulus of rail and $I$ is the moment of inertia of the rail cross-section). The critical train speeds for the subway cars was calculated at 56 mile/hr based on the properties of the rail and...
subway cars as summarized in Table 1. All subway trains travelling through the area of interest were below the critical train speed.

### Table 1 – Physical Properties of Train and Rail used for Calculation

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per unit length (lbs/yd)</td>
<td>114.7</td>
</tr>
<tr>
<td>Cross-sectional area (sq.in)</td>
<td>11.25</td>
</tr>
<tr>
<td>Moment of inertia (in²)</td>
<td>65.9</td>
</tr>
<tr>
<td>Modulus of elasticity (PSI)</td>
<td>$30 \times 10^6$</td>
</tr>
<tr>
<td>Wheel diameter (in)</td>
<td>28</td>
</tr>
<tr>
<td>Weight of a car in service (lbs)</td>
<td>110463</td>
</tr>
<tr>
<td>Weight of a wheel (approximate, lbs)</td>
<td>800</td>
</tr>
</tbody>
</table>

The length of the wheel-flat was estimated from the calculated wheel-flat height based on the total change of momentum due to the impacts as shown in following formula [7]:

$$m_{eq} \Delta V = V m_{eq} \sqrt{2h/a},$$  \hspace{1cm} (5)

where $m_{eq}$ is equivalent mass ($\approx 0.4 \rho_t$), $V$ is train speed and $h$ is height of wheel flat.

### RESULTS and DISCUSSION

#### Train Speed Calculation

The train speed of each pass-by was calculated with two methods. The first utilized the optical sensor, which detected when and for how long the train pass-by occurred. From this, the speed of the train was calculated based on a nominal train length of 448ft. The second method was to perform the DWT on the data from the invert sensor. This technique allowed detecting the axles and calculating speed for every bogie. The reported train speeds for each pass-by were averaged over all bogies.

Table 2 indicates that the train speed calculated by DWT with acceleration or optical sensor correlates well with the output from the existing force based wheel-flat detection system. The optical sensor based calculation for train speed matches slightly better than that calculated from the invert accelerometer. The position of the optical sensor and accelerometer sensor are different and could be responsible for the slightly different results in train speed. Regardless, the average, minimum and maximum train speed difference between the optical sensor, accelerometer calculation and the existing system is well within acceptable tolerances.
Table 2 - Train Speed Calculation Results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Optical Sensor mile/hr</th>
<th>Accelerometer via DWT mile/hr</th>
<th>Existing Wheel-flat System mile/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>38</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Minimum</td>
<td>31</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>Maximum</td>
<td>44</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Potential Existence of a Wheel-Flat and Estimated Length**

As detailed earlier, the existence of a wheel-flat would typically generate repetitive impacts on the rail and could be detected with the cepstrum analysis. This analysis had been carried to detect the potential presence of a wheel-flat by searching for the first echo of the wheel-flat. The results were compared with trains flagged with a warning, alarm or emergency category from the existing forced based wheel-flat system.

As previously mentioned, the overlap of wheel diameters and the separation distance between axles on the same bogie creates a potential error between identifying which wheel on a bogie has a defect. Therefore, the results for the cepstrum analysis presented from the accelerometer based wheel-flat detection system were shown by per bogie. A refinement to this algorithm is possible to minimize the error for the cepstrum analysis.

The proposed accelerometer based wheel condition detection system measured a total of 88 trains, of which 79 were available for analysis. The remaining trains were rejected due to low train speeds. A total of 79 trains were also measured with the existing wheel-flat detection system, and were time aligned with the with the accelerometer measurement data. A total of 12 trains were flagged with notifications from the existing system during the measurements.

Table 3 summarizes the comparison of some results between the existing system and the acquired accelerometer data as part of this study.
### Table 3 - Comparative Results for Trains

<table>
<thead>
<tr>
<th>Car ID</th>
<th>Train Speed (mile/hr)</th>
<th>Train Axle No</th>
<th>Wheel Location</th>
<th>Peak Acc. (g)</th>
<th>Potential of Wheel Flat</th>
<th>Wheel-flat Length (Inch)</th>
<th>Train Axle No</th>
<th>Wheel Location</th>
<th>Wheel-Flat Categorization</th>
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<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>23/24</td>
<td>Right</td>
<td>186</td>
<td>Yes</td>
<td>1.8</td>
<td>23</td>
<td>Right</td>
<td>Alarm</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>108</td>
<td>Yes</td>
<td>1.3</td>
<td>23</td>
<td></td>
<td>Alarm</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td></td>
<td>Emergency</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>11/12</td>
<td>Left</td>
<td>134</td>
<td>Yes</td>
<td>1.3</td>
<td>10</td>
<td>Left</td>
<td>Emergency</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td>303</td>
<td>Yes</td>
<td>3.1</td>
<td></td>
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<td>Emergency</td>
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<tr>
<td>2</td>
<td>40</td>
<td>9/10</td>
<td>Left</td>
<td>184</td>
<td>Yes</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td>230</td>
<td>Yes</td>
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<td>-</td>
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<tr>
<td></td>
<td>40</td>
<td></td>
<td>Right</td>
<td>78</td>
<td>Yes</td>
<td>0.7</td>
<td>12</td>
<td>Right</td>
<td>Information</td>
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<td></td>
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<td></td>
<td>82</td>
<td>Yes</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
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</table>

Car #1 generated many flags from both bogies, both sides and all axles. This could in part be due crosstalk between left and right sides of the car as well as crosstalk between the axles on the same bogie and side. A wheel with a large flat can easily generate high vibration levels picked up by the sensors on the other rail or for the second wheel on the same side. For both pass-bys, the system detected a wheel-flat for the right side of the rear bogie of this car. The peak vibration levels can be significantly different as it depends on where the wheel-flat is located physically on the wheel. Regardless, the system has predicted a wheel flat with a length of 1.3~1.8inch. The existing system also picked up a wheel-flat at the same location and flagged it with an alarm for the second last wheel and an emergency for the last wheel.

Car #2 clearly has a wheel-flat as per the physical inspection results as shown in Figure 3. The results as shown in Table 3 indicate that both the existing and the accelerometer based system detected its presence on the front left bogie. From the accelerometer
based system, a wheel-flat length ranging between 1.3~3.1inch was predicted with an average of 2.1inch which correlates well with the physical inspection of the wheel.

For the rear bogie, the accelerometer based system also detected a wheel-flat of ranging between 1.8~2.3inch lengths on the left side. From an inspection of the time signal and a listening test, the wheel-flat character appears to be present on the rear bogie of this car as well. However, the existing system did not pick up this wheel-flat.

For the same bogie, the right side rear axle was flagged with Information signs. Also, the accelerometer based system identified a distinct repetitive nature for the right side of the bogie. An explanation was some cross-talk between the left and right side. As shown below in Figure 4, the acceleration levels measured at Channel 1 (right-Side, in red) and Channel 2 (left side, in green) indicate that a similar pattern is found between the two with different amplitudes and a very small delay representing transmission time from north to south rail. The use of the axle-mask windows allows the accelerometer method to differentiate between left and right sides of the train and hence minimize the effects of cross-talk from large wheel-flats.

Figure 3: Car #2 Wheel-Flat on Left Axle #9/10
A small subset of cars were also identified to potentially have a wheel-flat, but not as large as those previously mentioned. This analysis proves useful as it may help in identifying an appropriate threshold for determining when to send cars to the maintenance yard for service. Table 4 summarizes the results of the remaining cars with potential wheel-flats.

Figure 4: Acceleration Levels on North and South Rail for Car #2
Table 4 - Identified Wheel-flats Accelerometer based System

<table>
<thead>
<tr>
<th>Car ID</th>
<th>Train Pass-by Number</th>
<th>Train Speed mile/hr</th>
<th>Train Axle Number</th>
<th>Wheel Location</th>
<th>Peak Acceleration (g)</th>
<th>Signal Energy (g²)</th>
<th>Potential of Wheel-Flat</th>
<th>Wheel-flat Length inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>21</td>
<td>39</td>
<td>21/22</td>
<td>Left</td>
<td>108</td>
<td>48</td>
<td>Medium</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>38</td>
<td>1/2</td>
<td>Right</td>
<td>79</td>
<td>52</td>
<td>Medium</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>40</td>
<td>3/4</td>
<td>Right</td>
<td>82</td>
<td>68</td>
<td>Medium</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>97</td>
<td>82</td>
<td>Medium</td>
<td>0.9</td>
</tr>
</tbody>
</table>

An inspection of the time signal and a listen test of the recorded signals, along with a measured repetitive signal, indicates that a potential does exists for smaller wheel-flats ranging between 0.7-1.0 inch for Cars #3, #4 and #5. An examination of the output of the existing system for these trains yields a range between 1.64 and 2.22 dynamic-to-static ratio which will not generate an Information flag according to the existing threshold levels.

If the thresholds were reduced to provide an Information flag when the dynamic-to-static ratio was set to 2.0, additional flags would obviously be sent, but there still may be smaller to medium wheel flats that would not be picked up by the existing system, such is for car #5 listed above which outputted only a 1.64 dynamic-to-static ratio. The thresholds should be further investigated to determine the appropriate levels based on a ‘State of Good Repair’ criteria typical for commuter rail systems.

CONCLUSION

An accelerometer based wheel-flat detection system for a subway transit system was developed utilizing signal processing techniques. An in-service measurement was conducted on a subway line and the results were compared with a force sensor based system.

It was concluded that this proposed accelerometer based system was able to identify specific wheels with large wheel-flats and quantify the length of wheel flat. Since this accelerometer based system does not require any alternation of existing track, the installation cost can be significantly less than the force sensor based system. The accelerometer based system has the potential for identifying smaller wheel defects and characterizing whether the defect is from a wheel-flat or from high levels of roughness. It also has been shown that it crosstalk effects between left and right sides of the train can be minimized. In addition, since it was experienced that listening the sound of recorded data was useful for the investigation of this analysis, combining
sound analysis module to this proposed accelerometer based system could be a benefit to obtain more accurate results in the future.

This study concluded that in general, the accelerometer based system correlates well with the existing force based wheel-flat detection system when detecting large wheel flats. The accelerometer based system also has the potential to detect and characterize different types of defects based on advanced signal processing techniques shown in this study.

The existing wheel-flat detection system is identifying trains that have large wheel flats but further measurements and analysis are recommended to confirm any reduction in surface vibration as a result of being able to identify these trains during service and re-direct them to the yards for maintenance. Further study is also recommended in terms of determining acceptable levels to keep the transit system in a state of good repair moving forward.

REFERENCES


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Table 2 - Train Speed Calculation Results
Table 3 - Comparative Results for Trains with Warning or Emergency Flag
Table 4 - Identified Wheel-flats Accelerometer based System
Development of an Accelerometer Based Wheel-Flat Detection System for a Subway Transit System in Toronto

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Tim Preager, B.A.Sc., P.Eng.

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Introduction

Subway train generated noise and vibrations
- moving static loads on rail and above inverts
- rail corrugations
- rail/wheel roughness
- impacts due to rail joints
  - impact due to wheel-flats
    - damage on wheel and rail
    - identify and remove

Introduction (continued)

Wheel condition monitoring systems

<table>
<thead>
<tr>
<th>Static/Dynamic Load Measurement</th>
<th>Dynamic Response Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Type</td>
<td></td>
</tr>
<tr>
<td>Strain gauge, fiber-optic</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>cable, force sensor</td>
<td></td>
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<td>Advantage</td>
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<tr>
<td>Simple calculation algorithm,</td>
<td>Cost efficient (installation, system), Simple system</td>
</tr>
<tr>
<td>direct load measurement</td>
<td></td>
</tr>
<tr>
<td>Disadvantage</td>
<td></td>
</tr>
<tr>
<td>Expensive (installation, system), Complicate system</td>
<td>More data processing power</td>
</tr>
</tbody>
</table>

Analysis Procedure (Aercoustics)

1. DWT of acceleration signal to locate axles and calculate speeds
Analysis Procedure (Aercoustics)

1. DWT of acceleration signal to locate axles and calculate speeds
2. Determine peak acceleration per axle
3. Determination of existence of periodic impacts with Cepstrum analysis
4. Other ongoing potential analysis
   - Wheel roughness
   - Extent of wheel-flats (height/depth)
   - Out-of-roundness of wheel

Results and Discussion

Train speed estimation results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Optical Sensor</th>
<th>Accelerometer via DWT</th>
<th>Existing Wheel-flat System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mile/hr</td>
<td>mile/hr</td>
<td>mile/hr</td>
</tr>
<tr>
<td>Average</td>
<td>38</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Minimum</td>
<td>31</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>Maximum</td>
<td>44</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Wheel-flat estimation results (car #1)

<table>
<thead>
<tr>
<th>Car ID</th>
<th>Train Speed</th>
<th>Train Axle No</th>
<th>Wheel Location</th>
<th>Wheel-flat Categorization</th>
<th>Wheel Axle No</th>
<th>Wheel-flat Categorization</th>
<th>Peak Acceleration</th>
<th>Potential of Wheel Flat</th>
<th>Wheel-flat Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Right</td>
<td>23</td>
<td>23/24</td>
<td>Emergency</td>
<td>Right</td>
<td>186</td>
<td>Yes</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Right</td>
<td>23</td>
<td>24</td>
<td>Emergency</td>
<td>Right</td>
<td>108</td>
<td>Yes</td>
<td>1.3</td>
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</tr>
</tbody>
</table>
## Results and Discussion (continued)

### Wheel-flat estimation results (car #2)

<table>
<thead>
<tr>
<th>Car ID</th>
<th>Train Speed</th>
<th>Train Axle No</th>
<th>Wheel Flat Categorization</th>
<th>Car ID</th>
<th>Train Speed</th>
<th>Wheel Flat Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>40</td>
<td>10</td>
<td>Emergency 9/10 Left</td>
<td>1</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
<td>Emergency 11/12 Left</td>
<td></td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
<td>Emergency 44</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>40</td>
<td>-</td>
<td>Emergency 40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Benefits of Aercoustics Accelerometer based System

1. **Cost Efficient due to**
   - less hardware (2–3 sensors; no speed sensor)
   - less maintenance cost
   - less installation cost (no-invasive installation)

2. **Customizable**
   - additional metrics can be programmed (provide more information and accuracy)
   - can be tailored to transit or heavy-haul

3. **Easy to Relocate**

### Closure

- Developed an accelerometer based wheel condition monitoring system
- Identified and quantified wheel flats on specific wheel(s)

Results from accelerometer based system agrees well with force sensor based system

Accelerometer based system can be a cost effective solution for wheel-flat monitoring

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