AC 2008-1330: AN INVESTIGATION OF ACCELERATION AND JERK PROFILES OF PUBLIC TRANSPORTATION VEHICLES

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An Investigation of Acceleration and Jerk Profiles of Public Transportation Vehicles

Abstract

The acceleration and braking profiles of several public transportation vehicles were investigated as part of an independent undergraduate student research project in Electro-Mechanical Engineering Technology. In particular, vehicles in which the passengers are often required to stand while the vehicle is moving were studied. These vehicles include city buses and subway trains. Vehicle acceleration, either positive or negative (braking), and the time rate of change of acceleration, jerk, can have a significant impact on the safety and comfort of passengers. The effects of acceleration and jerk are especially troublesome for passengers that either choose to stand or must stand in the vehicle because no empty seats are available. A standing passenger has a higher center of mass and smaller base footprint than one that is seated. The standing position is also less stable than the seated position. Therefore as the vehicle accelerates or changes its acceleration, standing passengers must exert significant forces with their limbs to maintain their balance. In this paper, the instrumentation and software used to measure the acceleration and jerk of some public transportation vehicles are presented and discussed. Instrumentation hardware and software typically used in an engineering technology laboratory was used for these measurements. The data obtained from the testing of several vehicles is analyzed and interpreted using software and techniques familiar to undergraduate engineering technology students. Fundamental dynamics associated with the human passengers is also presented and discussed. Careful control of the acceleration and braking profile of the vehicle can greatly improve the comfort and safety of the passengers. A suggested instrumentation and display system to help drivers control the acceleration profiles to improve passenger safety is presented. This project utilizes many aspects of the course and laboratory work of the four-year electro-mechanical engineering technology program. No human subjects were used in this study.

Introduction

Every year, commuters travel more than 20 billion miles by bus and 9 billion miles by commuter rail in the United States[1]. During the national average 24.4 minute commute to work, there are many factors affecting ride comfort[2]. Some of these factors are noise, temperature, humidity, and motion[3]. The factor of motion, including acceleration and jerk, will be examined as a transit vehicle comes to a complete stop. As the vehicle reaches zero velocity and does not reverse direction, the acceleration exhibits a very rapid (nearly discontinuous) change. This rapid change in acceleration imposes a large *jerk* on all elements in motion with the vehicle, including its passengers. Note that jerk is also referred to as *jolt* which is equally descriptive of this action. To better understand the physics of the linear motion experienced by ground vehicle passengers, a description of displacement, velocity, acceleration, and jerk will be presented. This information will be applied to the dynamics of the average commuter's reaction time and balance retention.

Acceleration data was acquired from several public transit vehicles using an accelerometer and a LabJack data acquisition unit in conjunction with a laptop computer. A custom software application (virtual instrument) to control the measurement system and process the acquired data was developed and implemented using LabVIEW. With this data, a comparison of vehicle motion and the ability of passengers to retain their balance as the vehicle comes to a stop are discussed. The results of this research will be examined to determine if passenger motion comfort and safety could be increased without significantly increasing transit time.

Physics of Linear Motion

Recall that the rate of change of displacement (r) with respect to time (t) is velocity (v). With displacement measured in meters and time measured in seconds, the velocity would have units of m/s.

$$v = \frac{dr}{dt} \tag{1}$$

The rate of change of velocity with respect to time is acceleration. This is also the second derivative of displacement. The resulting units of acceleration are m/s^2.

$$a = \frac{dv}{dt} = \frac{d^2r}{dt^2} \tag{2}$$

The rate of change of acceleration with respect to time is referred to as jerk. This is also the third derivative of displacement and thus has units of m/s^3.

$$j = \frac{da}{dt} = \frac{d^3r}{dt^3} \tag{3}$$

The relationship of displacement, velocity, acceleration, and jerk can be seen graphically in Figure 1. An object is shown as it approaches a velocity of zero. Initially the object had a constant negative acceleration. The displacement has been reduced at the beginning of the sample in order to show it on the same graph.

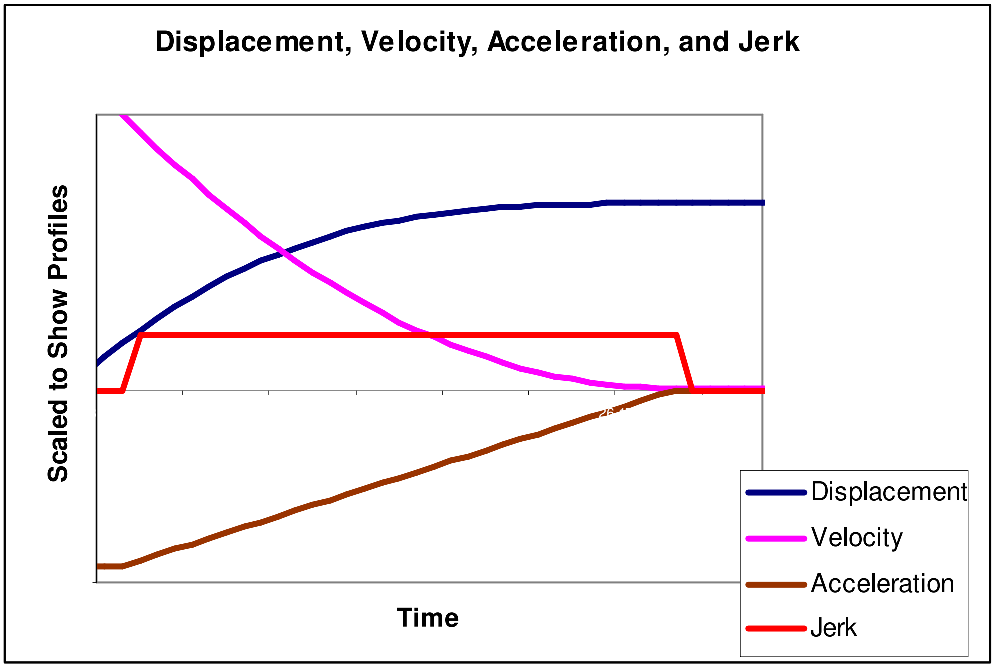

Figure 1. Relationship of the time derivatives of displacement

As shown, a constant positive jerk results in a linearly decreasing acceleration. Although this graph is unit-less, it shows a smooth velocity transition to zero. If the acceleration were steeper, the jerk would be larger over a shorter period of time. This would cause the velocity to transition from linearly decreasing to zero very quickly.

The components that create discomfort and instability for vehicle passengers are excessive acceleration, which results in excessive external forces, and excessive jerk which, together with reaction time, results in excessive or deficient human reaction forces. The magnitude of these components can be found by the mass (kg) of the object in motion.

$$Force = F = ma \qquad (\mathrm{kg\ m/s^2 = N}) \tag{4}$$

$$Yank = Y = \frac{dF}{dt} = m\frac{da}{dt} = mj \qquad (\mathrm{kg\ m/s^3 = N/s}) \tag{5}$$

The average freestanding human can withstand a constant acceleration of 0.93 $\mathrm{m/s^2}$ standing perpendicular to the acceleration with his feet in a wide stance[4]. If a vehicle accelerates at a higher rate, the passenger must hold on with his hands or sit down in order to avoid the danger of falling. The largest jerk an average human can withstand without losing his balance is about 0.60 $\mathrm{m/s^3}$ even if the maximum acceleration is not exceeded[4]. The average reaction time for an adult over 65 is around 400 ms [5]. If the acceleration changes (jerk) faster than he can react by keeping his center of gravity over his feet, he will not be able to keep his balance. The passenger's arms must withstand the F and Y above his freestanding capabilities by holding onto a railing to avoid falling. Higher jerk forces can occur for very short lengths of time and not be noticed by passengers as long as there is an equal and opposite component. An example is a high frequency vibration (displacement) on a train caused by a bump in the track.

Instrumentation Hardware

The instrumentation hardware utilized to record data on the transportation vehicles consisted of an accelerometer, a U12 LabJack USB data acquisition unit, and a laptop PC. The instrumentation system was designed to be battery powered, easily carried onto the vehicle, set up with little effort, easily operated, and quickly stowed when preparing to exit the vehicle. The equipment was also designed to be inconspicuous in a typical commuter transit vehicle setting.

The accelerometer was a MMA2260D ±1.5g X-Axis Micromachined Accelerometer manufactured by Freescale Semiconductor. The MMA2260D operates from a single 5 V power supply, has a sensitivity of 1.2 V per g and a zero-g output offset of 2.5 V. [6] These features made this accelerometer well suited for the measurement of transit vehicle parameters.

Figure 2 shows a schematic of the accelerometer printed circuit board. The components of the PCB were powered via the +5 VDC output of the LabJack. The PCB contains the filtering and protection components recommended by the manufacturer application notes as well as a simple unity-gain amplifier to serve as a buffer between the filter circuit and the LabJack input circuit. The terminal names shown (AI6, AI7, etc.) refer to LabJack connection terminals.

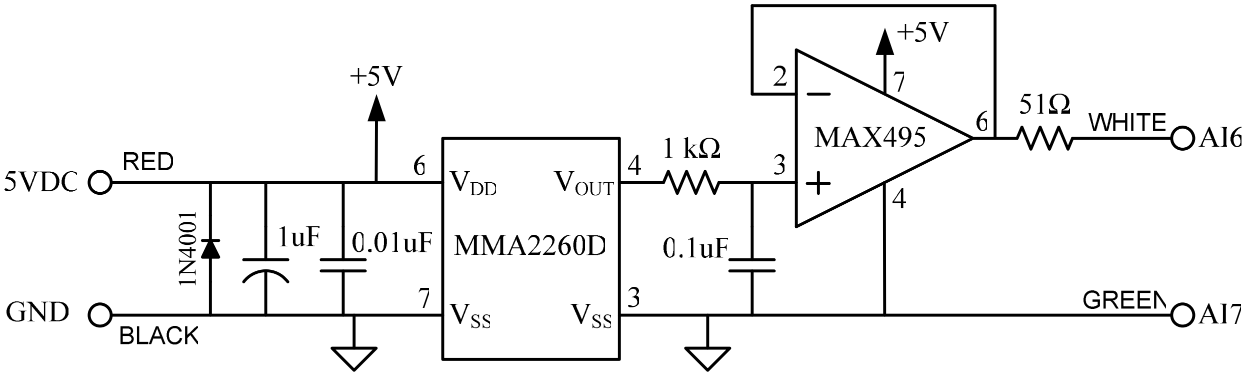

Figure 2. Accelerometer circuit board schematic

The LabJack has one 12 bit analog to digital converter which is preceded by a Programmable Gain Amplifier (PGA) and a signal multiplexer (MUX). For this application, it was configured to perform a differential voltage measurement between pins AI6 and AI7 (accelerometer board output) with a gain of 4. A gain of 4 produces a full-scale range of -5 V to +5 V. The scan rate was set to the LabJack's maximum of 1.2 kHz. The LabJack has internal memory that stores one data point per scan and transfers them to the PC via USB 2.0 in packets of 200 scans.

During testing on the public transit vehicle, the LabJack unit with the accelerometer PCB connected remained inside the laptop computer's carrying case. The carrying case was located on the floor of the vehicle in a predetermined position that would properly align the accelerometer's active axis with that of the vehicle's motion. The user was then seated in a passenger seat with the laptop computer placed on his lap. The USB cable connected the LabJack unit to the laptop computer.

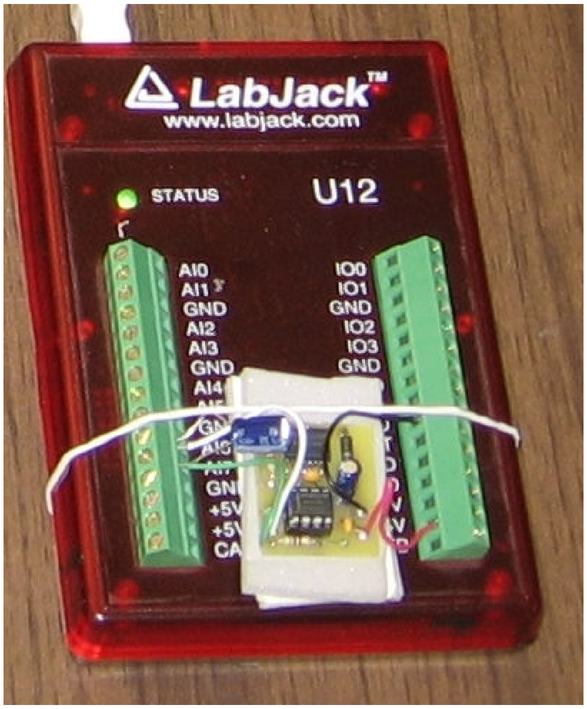

Figure 3. LabJack USB data acquisition unit with accelerometer PCB installed

Instrumentation Software

LabVIEW software was used to develop a virtual instrument (VI) to receive the scan data from the LabJack, display it, and save it as a spreadsheet file. The LabVIEW front panel user interface is shown in Figure 4. As shown in Figure 4, the user interface has control buttons to start and stop the data acquisition. These buttons were made large to allow easy positioning of the cursor over the button using the laptop touch-sensitive mouse while riding the moving vehicle. The top Waveform Chart area displays the near-real-time data (in 200ms packets) in strip-chart recorder style. Upon stopping the data acquisition, the entire data record is displayed in the lower Waveform Graph area to allow the user to accept or reject that record before saving it to a spreadsheet file.

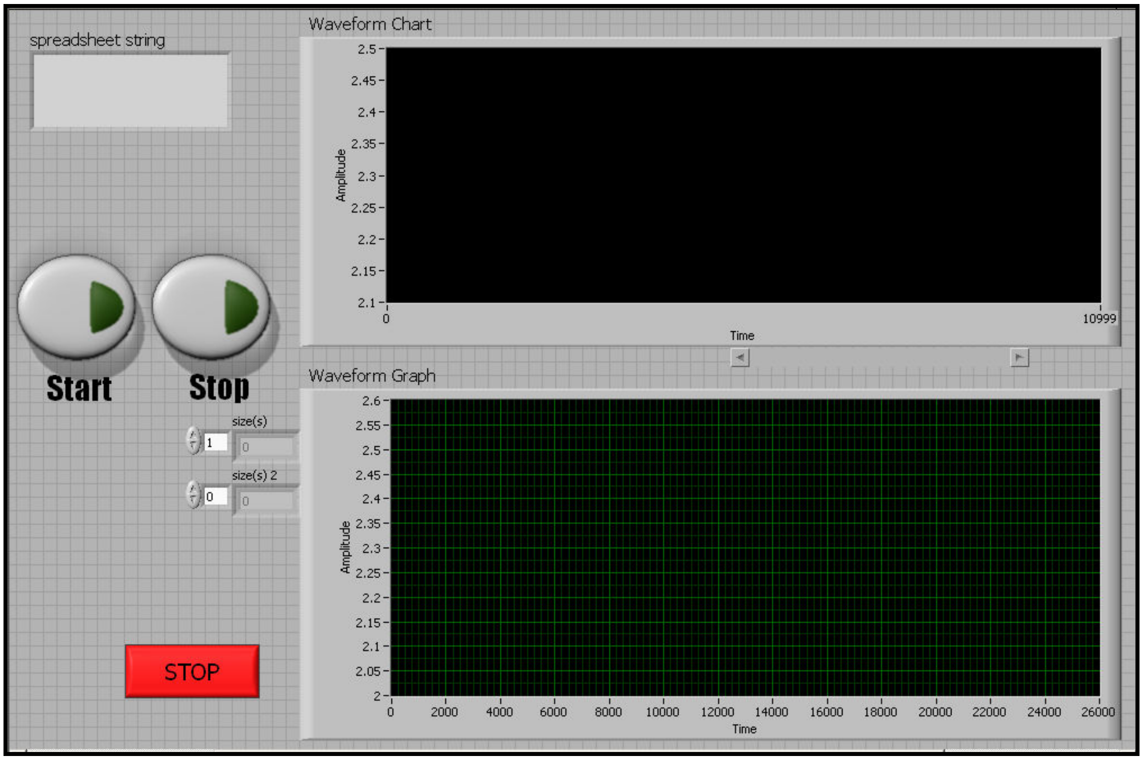

Figure 4. LabVIEW front panel user interface for data acquisition VI

Figure 5 shows the LabVIEW Block Diagram for the vehicle acceleration data acquisition VI. Once the program is started, everything inside the While Loop runs until the System Stop button is clicked (the red stop). To take data, the start button is clicked. This starts a Case Structure which initializes the LabJack with an AIStreamStart VI. The input data is passed from the LabJack through a Stacked Sequence Structure to another While Loop. The While Loop contains an AIStreamRead VI that receives the packets from the LabJack. The loop continues appending the data and displaying it on the Waveform Chart until the stop button is clicked. At this point, the accumulated data is displayed on the Waveform Graph and saved to the PC hard drive as a spreadsheet file.

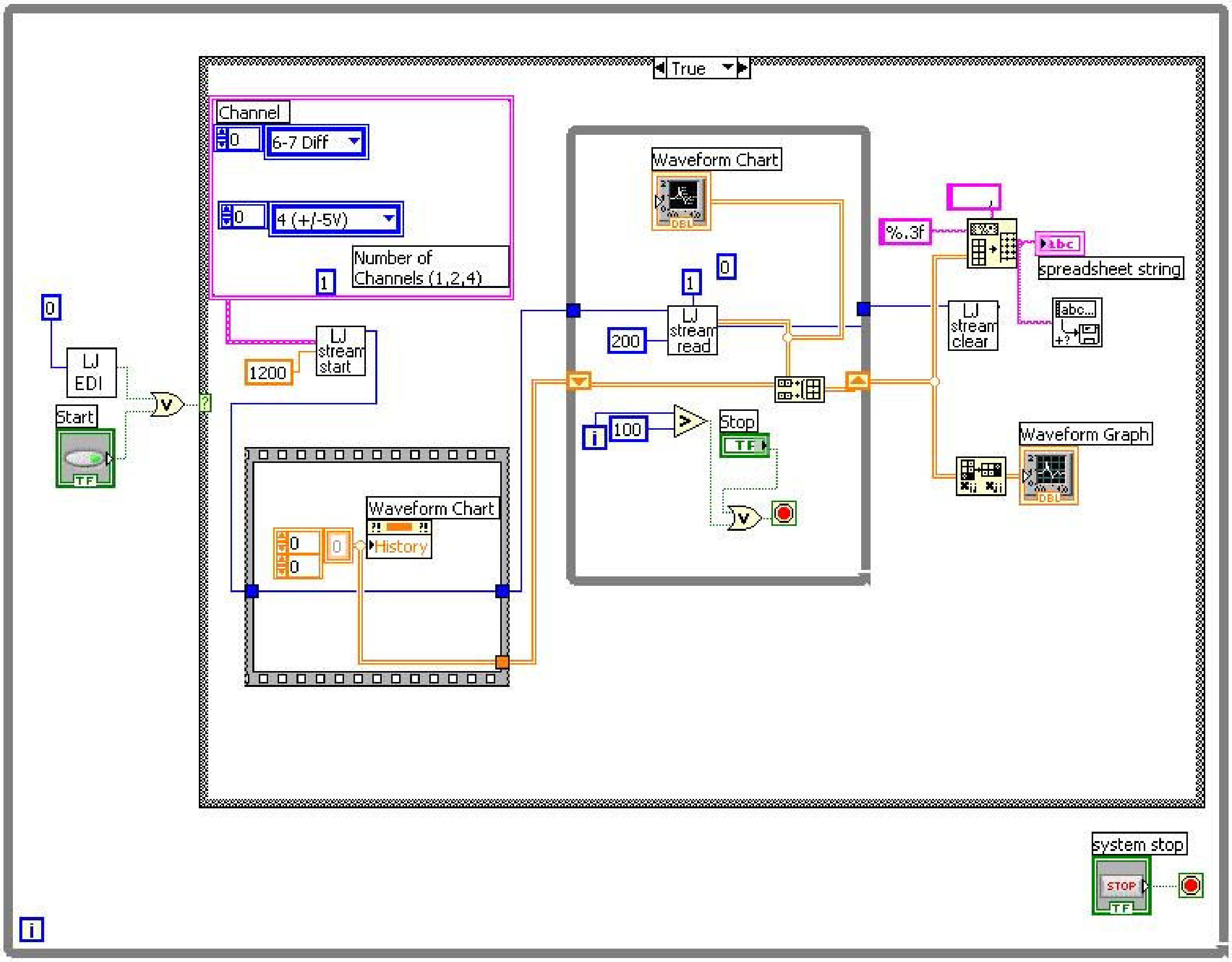

Figure 5. LabVIEW Block Diagram

Results of Data

Data was recorded on the MetroRail System in Washington D.C. The data to be examined was recorded on the Red Line Metro between Silver Spring and Metro Center. Figure 6 shows a photograph of a MetroRail train while Figure 7 shows a map of the MetroRail system. This rail system was chosen for its large ridership and one author's previous experience with jerky rides.

The sample shown in Figure 8 and Figure 9 was one of 44 samples. It was chosen because it clearly shows the acceleration and jerk of a typical stop. The acceleration data has been post-filtered in Microsoft Excel by applying a moving average filter with an aperture of 300 data points. At a sample rate of 1.2 kHz, 300 data points spans a time of 0.25 seconds. This averaging reduces the nuisance vibrations of the vehicle and provides a smoother acceleration profile from which the numerical derivative (jerk) can be obtained.

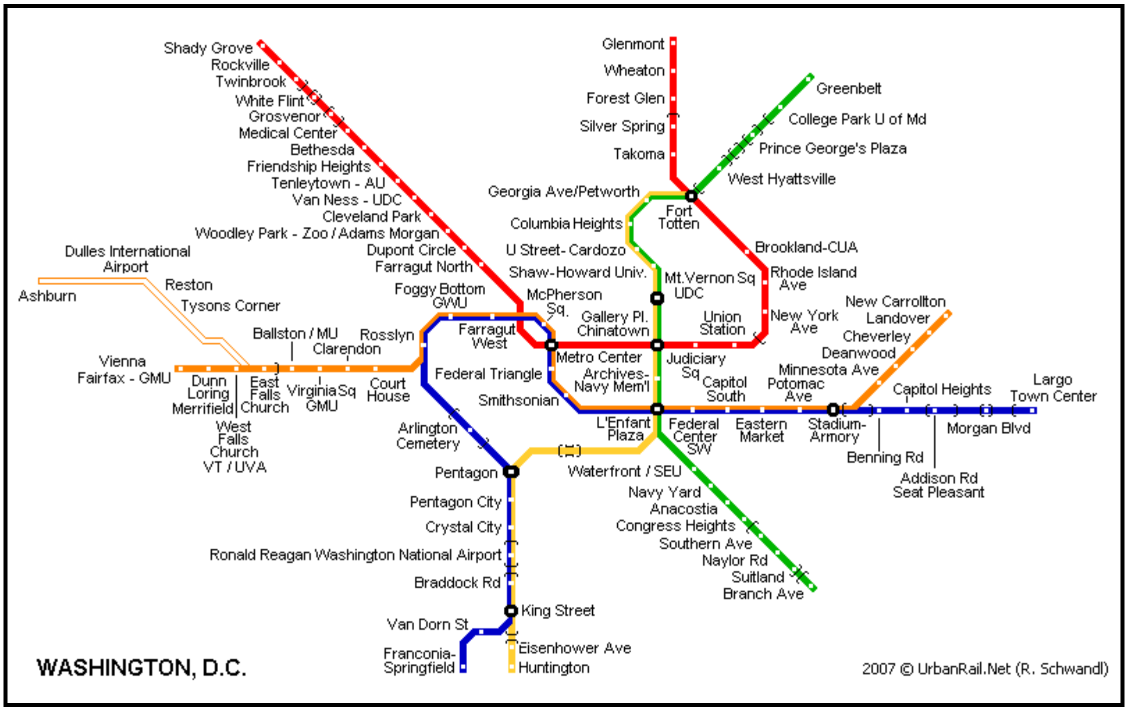

Figure 6. Metrorail System Map, Washington D.C.[8]

Figure 7. Red Line Metro, Washington D.C.[9]

As shown in Figure 8, the negative acceleration of the train as it approached the stop was slightly over twice the acceleration that can reasonably be handled by a passenger. If standing, the passenger would require support to avoid falling. As shown in Figure 9, the jerk is also quite significant peaking at 12.8 m/s^3. This, in addition to the high acceleration, would make it nearly impossible to avoid falling without support. The largest magnitude of the acceleration occurs roughly over the last two seconds of motion. If this were reduced, the jerk would not be nearly as significant. This shows that the comfort of transportation could be significantly improved without significantly increasing travel time.

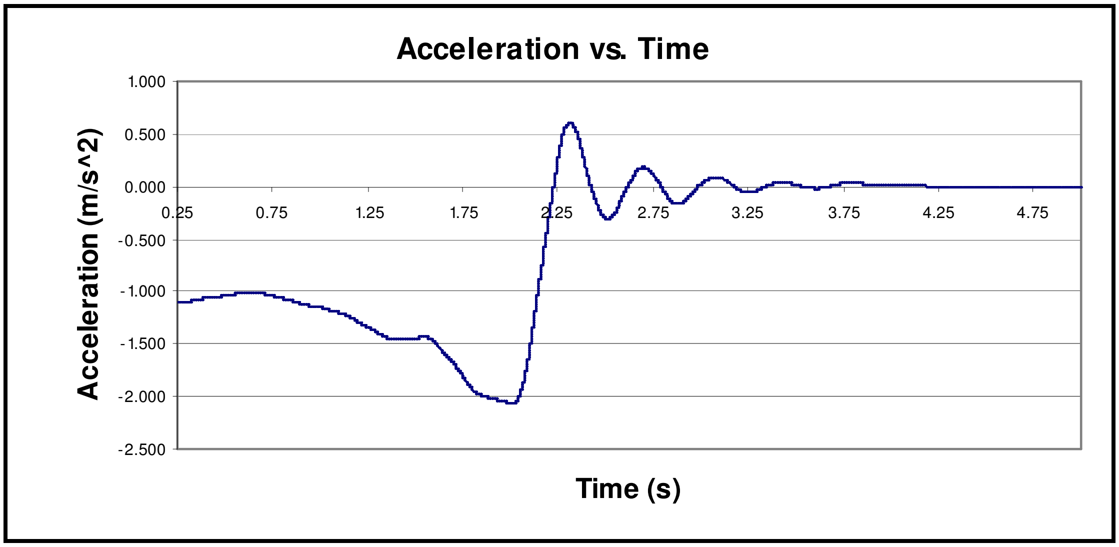

Figure 8. Acceleration Data from Red Line Metro

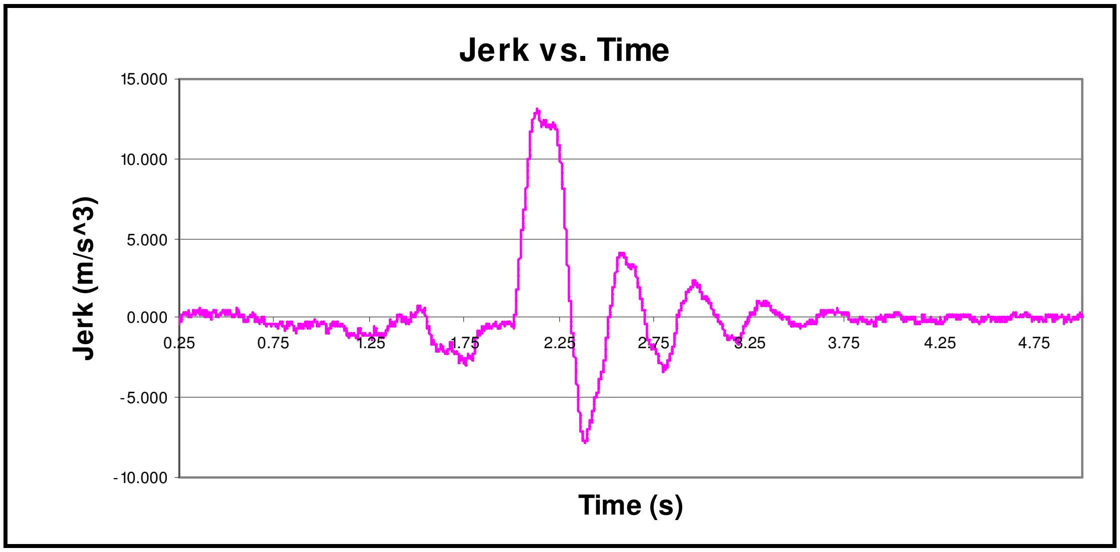

Figure 9. Jerk data from Red Line Metro

Conclusions

A simple instrumentation system was presented for the measurement of acceleration profiles associated with mass transit vehicles. The data obtained from this system correlates well with the observations of passengers on these vehicles. Also apparent in the data is evidence for concern for passenger comfort and safety. For rail systems such as the MetroRail in which the drive is completely electric, controls could be implemented to automate the acceleration and braking profiles to better conform to established levels of passenger comfort.

In order to reduce acceleration and jerk, a dedicated control system or a simple operator warning system could be implemented. For both systems, the key parameter that would be needed, together with the acceleration, is the speed of the vehicle. The vehicle speed is already available via the speedometer system. For a manual operator warning system, a simple digital or analog gauge would indicate the current passenger comfort zone as shown in Figure 10. The profile shown in Figure 10 was created using a maximum jerk of 0.6 m/s^3 and maximum acceleration of 0.9 m/s^2. These are the largest values a commuter can withstand without falling as defined earlier. As shown, the maximum deceleration can be maintained all the way down to slightly below 3 km/h. At this point the deceleration must be reduced to avoid exceeding the maximum jerk.

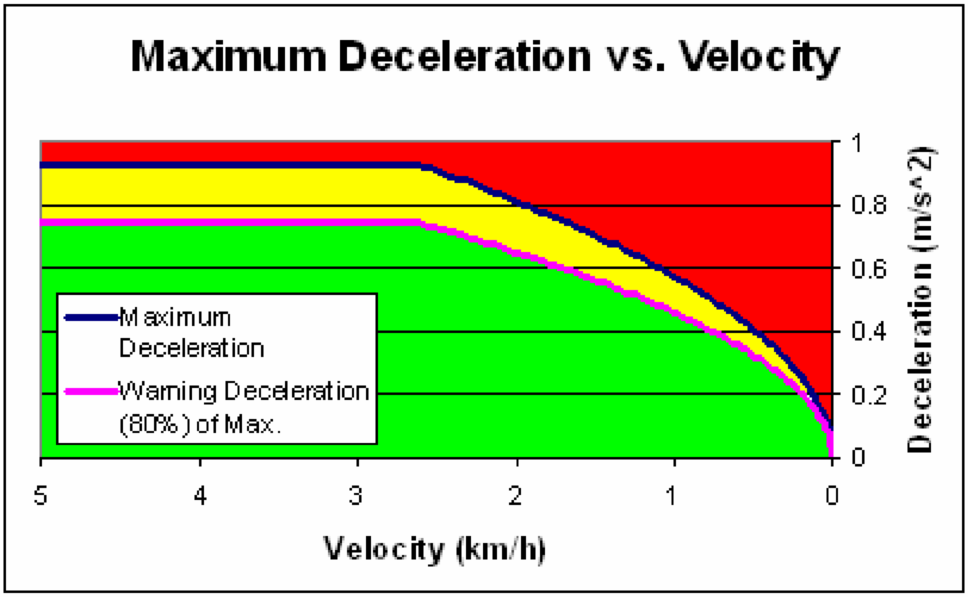

Figure 10. Maximum Deceleration Comfort Zones vs. Velocity

A dedicated control system would be more complex. As with the manual operator warning system, the vehicle velocity and acceleration would be sensed and the jerk would be predicted. The only additional information needed is the displacement to the next stop and the maximum velocity. The control must be broken down into 7 phases as shown in Figure 11 and Figure 12.

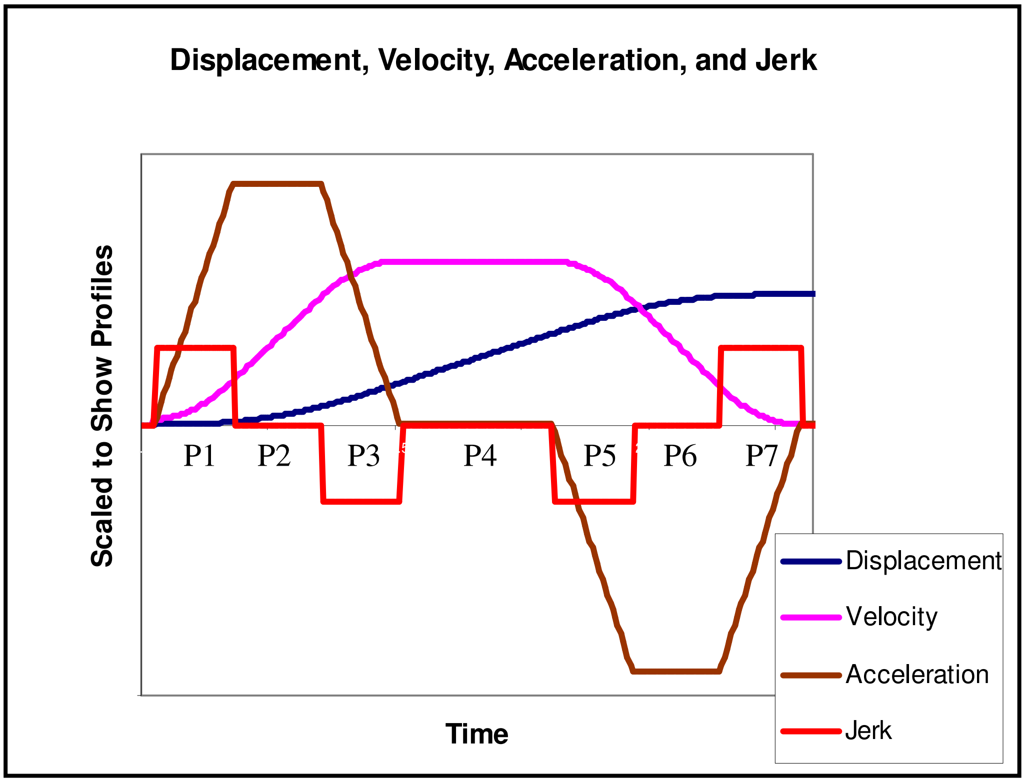

Figure 11. Control Phase Graph

	Jerk	Acceleration	Velocity	Displacement
Phase 1	Constant Max.	Increasing	Increasing	Increasing
Phase 2	Zero	Constant Max.	Increasing	Increasing
Phase 3	Constant Min.	Decreasing	Increasing	Increasing
Phase 4	Zero	Zero	Constant	Increasing
Phase 5	Constant Min.	Decreasing	Decreasing	Increasing
Phase 6	Zero	Constant Min.	Decreasing	Increasing
Phase 7	Constant Max.	Increasing	Decreasing	Increasing

Figure 12. Control Phase Chart

This entire system is driven by knowing the distance to the endpoint and back solving to find where to begin accelerating and decelerating the train. As shown in Figure 12, the maximum acceleration and jerk (of either polarity) must never be exceeded. The onboard control software would then compute the desired acceleration profile to meet the target operating point (either cruise speed for acceleration or a complete stop for deceleration). If implemented, the system would, of course, require the ability to be overridden by the operator.

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