Investigating Vibration Levels in a Neonatal Transport System

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Abstract— **The first standardized Neonate Patient Transport System is currently being deployed in the Province of Ontario. The equipment has been designed to meet various transport safety regulations; however, there is concern that this new equipment may result in elevated vibration of the patient. The research presented in this paper is part of our on-going efforts to understand and mitigate vibrations in the Neonate Patient Transport System. Our previous investigations focused strictly on indoor transportation of patients. Moving to actual road transport has presented challenges, due to the many confounding variables including driver behavior and road conditions. We therefore intend to transition to a controlled environment, using an industrial shaker table. This study reports on our efforts to instrument a ground ambulance and patient transport equipment to collect baseline accelerations to be used to drive the shaker table and verify accurate simulation of actual patient transport. Results indicate significant vibrations at low frequencies, resulting from both the underlying vehicle dynamics and the response of the patient transport equipment.**

Keywords— **neonatal transport, vibration, patient safety.**

I. INTRODUCTION

An Ontario taskforce recently completed a multi-year project to design the first provincial Neonate Patient Transport System (NPTS) [1]. This work was supported by the Provincial Council for Maternal and Child Health (PCMCH) and involved the four designated Ontario neonatal centers: McMaster Children's Hospital – Hamilton Health Science Centre, The Children's Hospital of Eastern Ontario (CHEO) in Ottawa, the Children's Hospital at the London Health Sciences Centre, and The Hospital for Sick Children in Toronto. The new NPTS has the goal of ensuring the safe transport of neonates, while simultaneously ensuring the safety of the transport team.

The NPTS meets a variety of appropriate standards, including CSA standards, Transport Canada standards for land and air ambulance, the Ontario Provincial Land Ambulance & Emergency Response Vehicle Standard, and IEC 60601 safety standards for medical electrical equipment. While "ISO 2631: Evaluation of human exposure to whole-body vibration" likely informed the ambulance design, no standards were available detailing safe vibration levels a neonatal patient can be exposed to for guiding the NPTS design. Following initial deployment of the NPTS, a number of transport teams perceived a qualitative increase in vibration levels. Studies have shown an increase in mortality and morbidity following neonatal transport [2]-[4]. Translational acceleration and vibration during transport is suspected to be an important causal factor [5]. This has motivated our group to initiate research to better understand the vibrations in the NPTS and to ultimately design ways to mitigate their effects.

In a previous study, we employed a custom data logger to investigate vibration levels, as well as the effect of different mattresses in the old and new transport systems during simulated indoor transport [6]. Results do indicate a statistically-significant increase in accelerations in the new transport system, particularly when the equipment crossed a floor expansion plate or entered/exited an elevator. For the latter case, when measured from the deck of the transport systems, accelerations were on average 3.57 times higher using the new NPTS compared to the transport system previously in use at CHEO. When measured at the head of the test mannequin, accelerations were reduced as compared to the NPTS frame (commonly referred to as the deck), indicating that the mattresses help to mitigate the vibrations from the deck to the patient; however, accelerations measured at the head remained higher for the new transport system.

While experiments involving on-road testing provide realistic conditions, results from several road tests in an actual ground ambulance resulted in significant variability in observed accelerations between experiments that could not be explained by the design parameter under test. For example, accelerations of the equipment deck differed between experiments, even when the sole change was to the mattress type within the incubator. It appeared that these differences were being caused by confounding factors such as changes in road conditions, driver behavior, traffic, etc. As such, we are exploring the use of a shaker table to provide a more controlled testing environment.
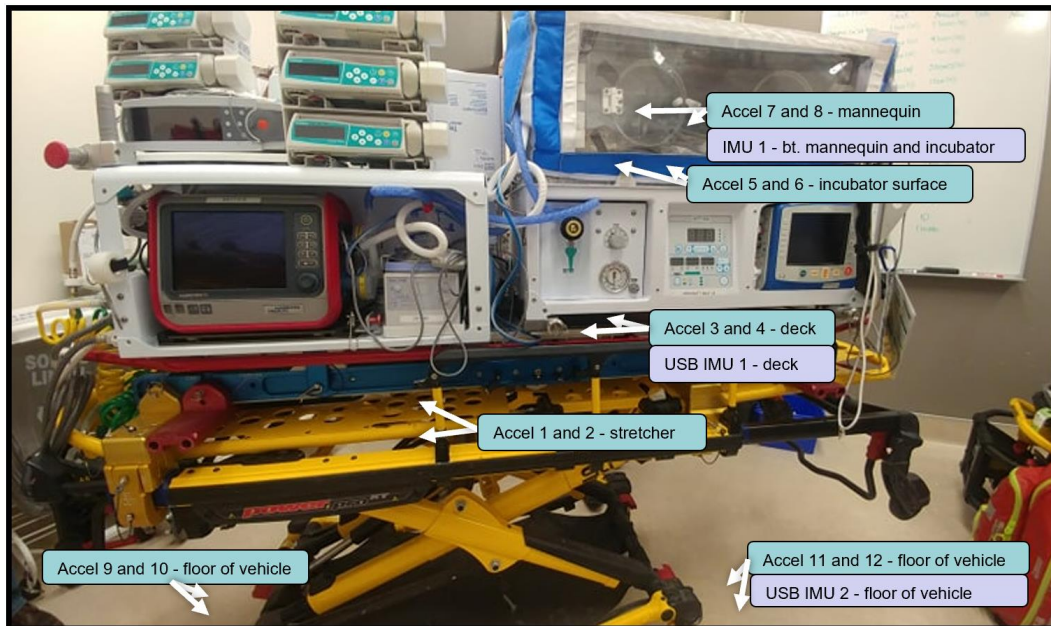
Figure 1: Sensor locations on NTPS and vehicle

The research presented in this paper is part of our ongoing efforts to understand and mitigate vibrations in the NPTS. Given the desire to transition data collection to a more controlled environment using a shaker table, an on-road experiment was designed and conducted to collect baseline acceleration data. These data will ultimately be used to drive the shaker table and confirm realistic simulation of actual ground transportation of neonatal patients.

II. METHODOLOGY

A. Sensors

The NPTS and the underlying Stryker stretcher were instrumented during the on-road experiment to quantify vibrations in terms of frequency and amplitude. Both tri-axial accelerometer data loggers (Gulf Coast Data Systems; http://www.gcdataconcepts.com/products.html) and inertial measurement units (IMU) comprising both tri-axial accelerometers and tri-axial gyroscopes (LORD, MicroStrain Sensing Systems; https://www.microstrain.com) were used. A 2.5kg neonatal mannequin was placed inside the incubator and was secured with a standard 5-point harness. Accelerometers were attached to the mannequin's forehead and chest, while an IMU was placed beneath the mannequin but above the mattress. Figure 1 illustrates the positions of all sensors on the equipment.

B. On-road experimental setup

Prior to data collection, common registration signals were recorded by each sensor such that their independent time stamps could subsequently be synchronized. This was achieved by temporarily attaching all sensors to a single stiff beam that was tapped thrice against a solid surface. This registration procedure was repeated at the conclusion of the experiment to ensure that all sensor clocks remained synchronized.

The NPTS and stretcher were loaded into a fleet-standard gas-powered ambulance provided by the Ottawa Paramedic Service. This vehicle is dedicated to the CHEO transport team and is equipped with a Stryker Power-LOAD® system (https://www.stryker.com/us/en/c/2018/more-power-to-you.html). Equipment within the NPTS, such as the ventilator and incubator heater, were not powered on. In addition to the sensors on the NTPS and stretcher, additional sensors were attached to the vehicle as follows. Accelerometers were attached to the vehicle floor at the front and rear of the mounting rail for the Power-LOAD® system. An IMU was attached to the vehicle floor at the horizontal-plane centre of gravity as estimated from the vehicle's published static axle loads. A second IMU was placed on the NPTS deck at the approximate location of its horizontal-plane centre of gravity. A GPS receiver was attached to the vehicle roof, while a secondary GPS (smartphone) was used in the vehicle cab.

In addition to collecting acceleration data, detailed event annotations were collected using a custom Android app created via the Temporal Event Annotation Framework [7]. Annotated events included the start and end of each road segment type, significant pot holes or speed bumps, starting and stopping the vehicle, and sensor synchronization events.

Video was recorded from three locations. First, a forward-facing video camera was placed in the cab to capture traffic conditions and vehicle behavior. Second, a camera was mounted on the vehicle ceiling recording the rear cabin of the ambulance including the entire NPTS. This captured all movements of the equipment relative to the vehicle. The third camera was affixed to the NPTS railing and recorded the contents of the incubator. This camera captured movements of the mannequin within the incubator, relative to the NPTS itself.

C. On-road data collection

The ambulance followed a route to capture data representative of in-city roads, high-speed highways, and traffic-free conditions (e.g. hospital Ring Road). See Figure 2 for an illustration of the data collection route. Here, different colours indicate different road segments. The paramedic driving the ambulance was instructed to drive as normal during an actual patient transport. The lights and sirens were not used, and all traffic laws were obeyed. For the freeway segment, the driver was instructed to target an average speed of 90 km/hr. In addition to the route illustrated in Figure 2, several laps were completed on two suburban roads each containing three speed humps (one road contained a series of three

Figure 2: Partial data collection route

standard sinusoidal speed humps and the other contained a series of three standard flat-topped sinusoidal speed humps) and three stop signs. On each lap, the target speed was increased by 5 km/hr, beginning with 15 km/hr and culminating in 45 km/hr.

III. Results and Discussion

On-road data collection was completed in Ottawa Ontario on 27 November 2018 between 10am and 2pm. Road conditions were typical, with some light snow cover and no significant traffic. Data were successfully recorded from all sensors, resulting in approximately 2 hours of data from 12 tri-axial accelerometers, 3 IMUs, 2 GPS, 3 video cameras, and an event annotation app. In total, 153 discrete event annotations were collected to annotate the acceleration data.

A. Analysis of recorded data

Analysis of the recorded data is ongoing. However, the z-component of the floor-mounted accelerometer has been examined since this will form the input data for the shaker table in subsequent experiments. The power spectral density for the rear floor-mounted sensor is provided in Figure 3. Peaks are visible at approximately 2 Hz, likely attributable to the vehicle chassis frequency, and at approximately 10.6 Hz, likely attributable to the wheel-hop frequency. Higher frequencies are of a lesser concern for patient safety, since the human body tends to filter out high frequencies. ISO 2631 reflects that while humans are sensitive to a relatively-wide range of frequencies, they are most sensitive in the 4Hz to 8Hz range.

As shown in Figure 4, a similar spectrogram is observed from the accelerometer attached to the mannequin's head inside the incubator. The second peak has shifted to a slightly lower frequency (9.8 Hz) and its amplitude has increased substantially (from -15 dB to 0 dB). This may represent amplification of vibrations in this frequency range due to resonance of the NPTS. Future experiments on the shaker table will establish the resonant frequencies of the NPTS and stretcher, to determine if these align with the frequencies at which the vehicle is exciting the equipment.

B. Future work

The on-road tri-axial accelerometer data collected here will be used to simulate on-road neonatal patient transport using an industrial shaker table, such that the ride experience can be reproduced reliably and to control for confounding variables. While the data from the vehicle floor (Stryker Power-LOAD® mounting rail) will be used to drive the
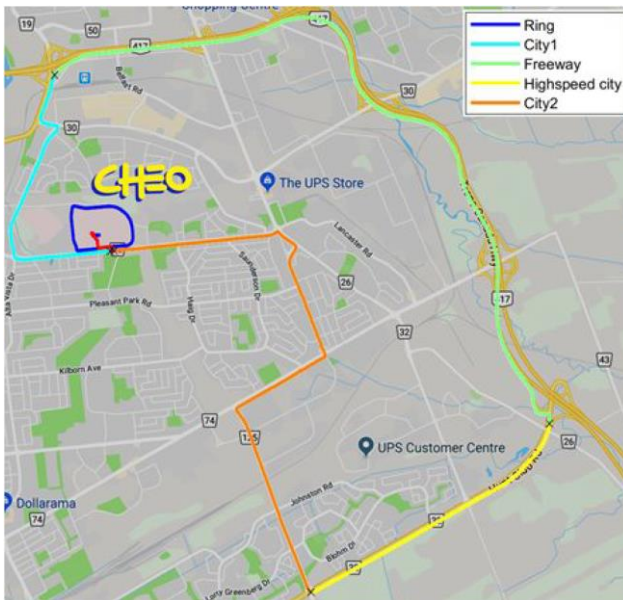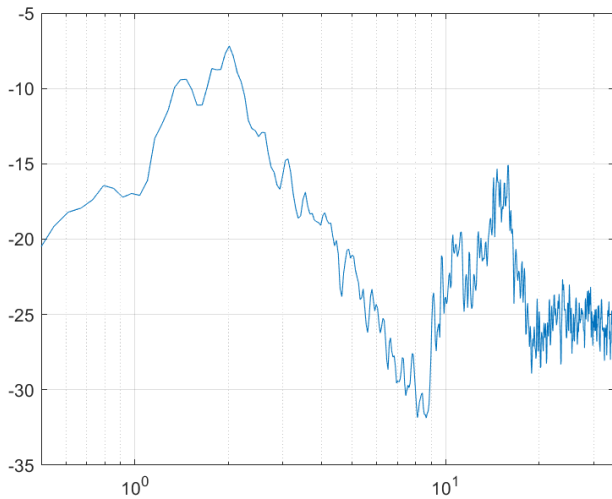
Figure 3: Power spectrum density of "Highway" road segment (80 km/hr) from the floor-mounted accelerometer. The x-axis is in Hz using a log scale, while the y-axis is in dB.
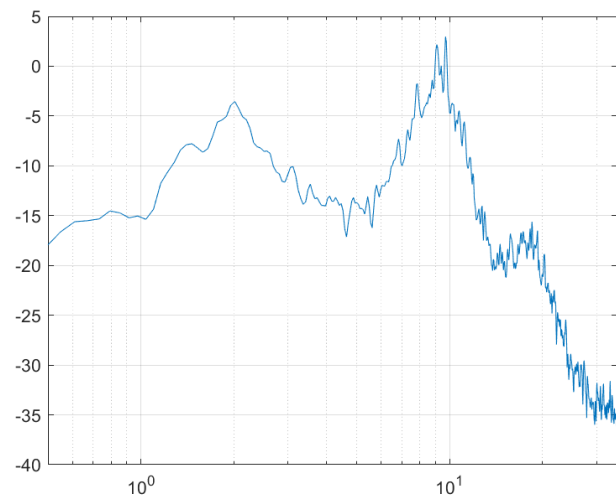

Figure 4: Power spectrum density of "Highway" road segment (80 km/hr) from the accelerometer mounted on the mannequin head in the incubator. The x-axis is in Hz using a log scale, while the y-axis is in dB.

shaker table, the accelerations measured at other points, including the stretcher, the incubator, and the neonatal mannequin, will be used to validate the fidelity of the simulation.

Experiments conducted using the shaker table will enable the exploration of several research questions, including:

- Which mattress type is most effective at reducing patient vibrations?

- Does patient mass impact vibrations?

- Does a supplemental head restraint reduce patient vibrations?

- How do vehicle speed and road type (highway/city) relate to patient accelerations?

- Is it possible to modify the equipment to reduce vibrations?

This investigation is ongoing with the expectation that results will provide insights regarding the vibrations in the Neonatal Patient Transport System and suggestions for how to mitigate vibrations, thereby further improving patient safety during transport.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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