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LATERAL VEHICLE ACCELERATION DUE TO LONGITUDINALLY TINED PORTLAND CEMENT CONCRETE PAVEMENT

Robert V. Rinehart
Michael A. Mooney

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16. Abstract
The objective of this study was to determine, via field measurements, the vibration characteristics of vehicle squirming (a.k.a. groove wander) – a phenomenon whereby vehicles experience lateral vibrations due to interaction between tire tread grooves and longitudinal pavement grooves. The report documents the details of a literature review of groove wander related studies as well as the results of field testing performed to measure vehicle and vehicle occupant vibrations during wander behavior. Recommendations are made about the development of a wander evaluation system for future Colorado Department of Transportation (CDOT) studies. Field testing was performed over two days on a 4.8km (3mi) stretch of I-70 between E-470 and SH 36 Airport Road using a 2000 GMC Safari cargo van belonging to CDOT and known to experience wander. Lateral accelerations were measured at several locations including the seat frame, seat cushion, seat back, and the passenger's head. Wander is measurable as a low-frequency, low-amplitude phenomenon. Typical wander behavior is observed in the frequency band 1-3Hz. The most effective sensor location to capture vibrations due to vehicle wander proved to be the passenger's head. This location takes advantage of the human body's amplifying and filtering characteristics. For the testing conducted here with acceleration measured on the passenger's head, wander was generally associated with acceleration peaks greater than 0.75 m/s^2 (0.076g); however, vibration magnitudes are dependent on many factors including sensor location, vehicle, tire type, and vehicle occupant characteristics and posture. The standard methods for evaluating human exposure to vehicle vibrations (ISO-2631) did not yield a reliable indication of wander. Given that other sources of lateral vibration (e.g., wind, bumps, steering input) can lead to similar acceleration behavior to that of wander, and the fact that vibration amplitudes are dependent on many factors, it remains important to have human input when performing wander assessment.

Implementation
Given the difficulty in reliably and consistently quantifying wander, CDOT should consider relying solely on human assessment. If the goal is to determine whether or not wander exists for a certain stretch of roadway, human judgment appears accurate and reliable, i.e., the existence or non-existence of wander is clear and obvious to a passenger. If it remains desirable to develop a standard method to measure and quantify wander (e.g., to compare different roadways or tining patterns), the following should be kept in mind:

- Wander is vehicle-specific, so any efforts to standardize wander measurement need to employ a consistent, specific vehicle.
- The best location to place an accelerometer to capture vehicle wander is the passenger's head.
- Since vibrations are subject and posture dependent, subjects (or possibly an anthropomorphic test dummy) need to be similar in size and filtering characteristics, and given specific instructions regarding posture.

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EXECUTIVE SUMMARY

This report presents the findings from the Colorado Department of Transportation (CDOT) Study 21.81 – Alternate Longitudinal Tining to Address Vehicle Handling. The objective of this study was to determine, via field measurements, the vibration characteristics of vehicle squirming (a.k.a. groove wander) – a phenomenon whereby vehicles experience lateral vibrations due to interaction between tire tread grooves and longitudinal pavement grooves. The report documents the details of a literature review of groove wander related studies as well as the results of field testing performed to measure vehicle and vehicle occupant vibrations during wander behavior. Recommendations are made about the development of a wander evaluation system for future CDOT studies.

Several studies from the tire design and manufacturing community dealing with wander were identified. The common belief is that wander is due to an imbalance of lateral force created by individual tire tread and pavement groove contacts. The modeling of this phenomenon is becoming advanced and is taking advantage of numerical techniques. The impetus of the research studies identified was to be able to predict the severity of wander. This is an area of ongoing research. Studies dealing with the characteristics of wander vibration and its affects on vehicle passengers were not found in the literature.

Standard methods for evaluating human exposure to vibration do exist. However, the literature indicates that they may yield unrepresentative results when dealing with low-frequency, low-amplitude events. The literature review also revealed several important insights relating to the transmission of vehicle vibrations to vehicle occupants, including that the human body amplifies lateral vibrations in the 0.5-2.0Hz range while attenuating higher frequencies and that humans are most sensitive to lateral vibrations in the range of 1.25-2.0Hz.

Field testing was performed over two days on a 4.8km (3mi) stretch of I-70 between E-470 and SH 36 Airport Road using a 2000 GMC Safari cargo van belonging to CDOT and known to experience wander. Lateral accelerations were measured at several locations including the seat frame, seat cushion, seat back, and the passenger's head.

Wander is measurable as a low-frequency, low-amplitude phenomenon. Typical wander behavior is observed in the frequency band 1-3Hz. The most effective sensor location to capture vibrations due to vehicle wander proved to be the passenger's head. This location takes advantage of the human body's amplifying and filtering characteristics. For the testing conducted here with acceleration measured on the passenger's head, wander was generally associated with acceleration peaks greater than 0.75 m/s^2 (0.076g). It is important to note that vibration magnitudes are dependent on many factors including sensor location, vehicle, tire type, and vehicle occupant characteristics and posture.

The standard methods for evaluating human exposure to vehicle vibrations (ISO-2631) did not yield a reliable indication of wander. The seat cushion sensor placement mandated by the standard did not prove reliable to quantify wander. The increases in lateral vibration from zones where wander was not observed to those where it was observed were small, and very high variation existed. Further, the levels of vibration encountered were well below those that the standard suggests are typically associated with discomfort.

Given that other sources of lateral vibration (e.g., wind, bumps, steering input) can lead to similar acceleration behavior to that of wander, and the fact that vibration amplitudes are dependent on many factors, it remains important to have human input when performing wander assessment. Human assessment of wander has proven to be a valuable component of the wander evaluation system. If measured acceleration data alone is used, false positives will likely exist.

Implementation Statement

Given the difficulty in reliably and consistently quantifying wander, CDOT should consider relying solely on human assessment. If the goal is to determine whether or not wander exists for a certain stretch of roadway, human judgment appears accurate and reliable, i.e., the existence or non-existence of wander is clear and obvious to a passenger. If it remains desirable to develop a standard method to measure and quantify wander (e.g., to compare different roadways or tining patterns), the following should be kept in mind:

- Wander is vehicle-specific, so any efforts to standardize wander measurement need to employ a consistent, specific vehicle.
- The best location to place an accelerometer to capture vehicle wander is the passenger's head.
- Since vibrations are subject and posture dependent, subjects (or possibly an anthropomorphic test dummy) need to be similar in size and filtering characteristics, and given specific instructions regarding posture.

CHAPTER 1: OVERVIEW

1.1 Introduction

In September of 1997, CDOT adopted a new texturing specification for its portland cement concrete (PCC) pavements. The new specification called for uniformly spaced longitudinal tining at 20mm (0.80in) intervals with the depth and width of 3.2mm (0.125in). The specification resulted from an FHWA-sponsored multi-state study conducted in part by CDOT in 1995 (Ardani and Outcalt 1995, 2000). The results of this study indicated that longitudinal tining, in addition to possessing adequate frictional properties, was easier to install and produced lower noise levels than CDOT's traditional transverse tining.

CDOT has received negative feedback (e.g., via phone calls and emails from motorists) concerning handling of vehicles on newly constructed PCC pavements textured with longitudinal tining according to the current specification. Motorists describe their vehicles as feeling unstable and jerking laterally while driving at highway speeds. This phenomenon, internally referred within CDOT as vehicle squirming and referred to in the literature as groove wander, does not occur on all longitudinally-tined PCC pavements and is not experienced by all vehicles. It is not known whether or not these handling issues are hazardous. Note that hereafter, to be consistent with the existing literature, the phenomenon will be referred to as wander.

In response to the negative feedback, a preliminary study was conducted in 2006 by the authors of this report to determine if wander was a measurable phenomenon. Triaxial acceleration was measured at the vehicle axle and body during traverses over roadways with and without wander behavior. The accelerometer mounted to the vehicle axle provided greater acceleration levels in general, with the exception of wander-induced acceleration where the vehicle body accelerations were greater. It was therefore recommended that future studies focus on measuring vehicle body accelerations. The study showed that vehicle wander was a 1-2Hz lateral vibration phenomenon and while wander is very noticeable to the human body it is difficult to quantify and difficult to separate from the many sources of vehicle vibration. Lateral acceleration behavior similar to wander was observed while driving on transversely-tined PCC pavement and on asphalt pavement. Therefore, the preliminary study concluded that relying solely on accelerometer data to detect and quantify wander would be challenging.

Given the somewhat inconclusive results of the preliminary study, further investigation was deemed necessary. The objectives of the current study were to:

I. Perform a thorough literature review to (1) determine if previous research studies regarding wander have been performed, and if so, to (2) summarize their findings and the current state of knowledge regarding this phenomenon.

II. Capture vehicle wander with onboard instrumentation and perform appropriate data analysis to discern the key characteristics that define wander (e.g., acceleration amplitude, frequency content).

III. Identify the optimal sensing system (i.e., sensor(s), location(s), data acquisition) and testing specifications necessary to capture wander behavior.

1.2 Summary of Report

This report contains 5 chapters. Chapter 2 presents a literature review of previous research studies performed to evaluate vehicle and vehicle occupant vibrations due to longitudinally tined PCC pavements, and the sensitivity of vehicle occupants to these vibrations. Chapter 3 details the experimental setup, including the specifications of the sensors and data acquisition equipment used, sensor locations tested, and the testing procedures employed. Chapter 4 presents the results of the field measurements, including the vibration characteristics of wander and the optimal sensing system needed to capture those characteristics. Chapter 5 summarizes the conclusions of the research and provides recommendations for future investigations of wander.

CHAPTER 2: LITERATURE REVIEW

2.1 Longitudinal Tining Induced Lateral Vehicle Vibrations

The first objective of this study was to conduct a review of the existing literature to determine if wander had been previously investigated. While the body of literature is quite thin in general, several studies from the tire engineering and manufacturing community dealing with this phenomenon have been identified. These studies refer to the wander phenomenon as groove wander, and from this point forward the term wander will be used to refer to the longitudinal tining induced lateral vehicle accelerations of interest here.

While thorough assessment and characterization of the vibrations due to wander have not been performed, or at least not published, several valuable insights have been gained. In the late 1960's and early 1970's the California Department of Transportation conducted studies regarding safety of motorcyclists riding on longitudinally tined and broom textured PCC pavements (Sherman et al., 1969; Spellman, et al., 1972). The studies were subjective and based on motorcycle operator input, concluded that safety was not impaired.

In 1977, Tarapinian and Culp published the first wander theory, that of Tread Element Trapping. They postulated that wander was due to interactions between individual tire tread and pavement grooves. The predominant tire tread of the time consisted almost solely of circumferential grooves and by tabulating the number of occurrences of tire and pavement tread coincidences their theory did an adequate job of predicting subjective severity of wander. The study showed a good correlation between the so-called Coincidence Index and a subjective discomfort rating. A similar theory was suggested by Doi and Ikeda (1985), but only took into account the edge tread grooves, neglecting inner grooves. Further development of the Tread Element Trapping theory was carried out by Oblizajek and Lauer (1984) who developed a laboratory device to assess the severity of wander. The lab device allowed for more detailed investigations but did not result in major modifications to the original theory.

Given that the majority of research was being conducted by tire companies, the focus of studies inevitably became predicting whether or not a given tire tread pattern would experience wander, and to what degree. In 2001, Peters outlined the weaknesses of the current theory, namely its inability to deal with newer, more complicated tread patterns and its general lack of accuracy by way of a large number of false positives (i.e., many tire tread patterns were falsely rejected because the theory predicted they would experience high severity wander, when field testing revealed that they did not). A new Lateral Stress Theory was proposed and a Finite Element Method (FEM) analysis tool was developed which took into account more complicated tread patterns (Peters, 2001). The premise of the new theory was that, on a grooved surface, portions of the tread overhanging pavement grooves create an imbalance of lateral force. As the tire tread-pavement groove contact changes, so to does this imbalance of lateral force, leading to wander. The new analysis tool removed the subjectivity from the assessment of new tread designs by employing computer-based numerical analysis rather than the human based analysis required by the Tread Element trapping theory. The Lateral Shear Stress Theory followed in the footsteps of the Lateral Stress Theory, and taking advantage of increased computational abilities in FEM, took into account even more complicated tire tread features, e.g., sipes commonly found in snow tires (Nakajima, 2003).

Even though the state of the art in predicting tire tread performance is becoming more advanced (e.g., Nakajima, 2003), one major complication exists in that even small deviations in tining pattern from those assessed by the tire companies invalidates their assessment (Mundl et al., 2008; personal communication, Marion Pottinger, Ph.D., P.E., formerly of Smithers Scientific, May 2009). Further, some studies are still being conducted to improve the reliability of groove wander prediction. New tire tread pattern features and lack of widespread consensus regarding the most effective way to model the problem are resulting in continued experimental studies (personal communications: Will Mars, Ph.D., P.E., Editor, Tire Science and Technology – The Journal of the Tire Society, May 2009; Chris Raglin, Senior Research Engineer, Cooper Tire & Rubber Company, May 2009). There is value in characterizing the lateral vibrations due to wander and in developing a measurement system that enables a more objective assessment of wander.

2.2 Human Exposure and Sensitivity to Vehicle Vibrations

In addition to the literature regarding groove wander (i.e., wander), valuable literature pertaining to evaluating vehicle and vehicle occupant vibration and the sensitivity of vehicle occupants to various vibrations has been identified. The research results pertinent to the current study are summarized in the following chapters.

Standard methods for evaluating human exposure to transportation induced vibration are published by both the British Standards Institute and the International Standards Organization (BS-6481, 1987; ISO-2631, 1997). In the case of evaluating vehicle vibrations these standard methods take several different acceleration measurements into account: vertical and horizontal acceleration at the seat back, seat rest, and floor. Depending on the standard, the most severe measurement may be used to gage discomfort (ISO-2631 only) or the various measurements may be combined to gage discomfort (BS-6481 and ISO-2631). In either case, different measurements are subject to frequency weightings depending on the sensor. However, there is not wide consensus on which methods are most appropriate and the weighting factors themselves are the topic of ongoing research (e.g., Parsons and Griffin, 1988; Paddan and Griffin, 2002; Mansfield, 2004; Griffin, 2007). Further, assigning levels of discomfort is an error prone process, with large variations existing between individual test subjects and due to posture changes in repeat tests with the same subject (Corbridge and Griffin, 1986; Paddan and Griffin, 1994; Lewis and Griffin, 1996). Finally, the standards themselves deal with human exposure to vibration in general and their application to vehicle ride comfort can be limited due to the factors listed above as well as the manner in which they weigh the frequency, direction, and duration of acceleration, especially for low-amplitude and low-frequency events like wander (Griffin, 2007). While these findings do not provide compelling reasons for employing the standard methods to attempt to quantify vehicle vibrations during wander behavior, Section 4.5 presents the results of analysis according to ISO-2631.

Several studies have been conducted to characterize the transmission of lateral vibrations to vehicle occupants. Studies involving 20 male subjects by Corbridge and Griffin (1986) and 12 male subjects by Paddan and Griffin (1988) showed that the maximum sensitivity to lateral vibrations occurs between 1.25-2.00Hz and that when vibration is measured at the head, the human body acts to amplify accelerations in the range of 0.5-2.0Hz while nearly completely attenuating vibrations above about 8Hz. Summarizing 14 different studies, Paddan and Griffin (1998) confirmed these results. Corbridge and Griffin (1986) indicate that at low frequencies, humans are three times more sensitive to lateral vibrations than to vertical vibrations, and indicate that for lateral vibrations in the 1-5Hz frequency range, sinusoidal vibrations above about 0.75-1.0m/s^2 are usually assessed as uncomfortable. In a study to define driver sensitivity to changes in vehicle response Strandemar and Thorvald (2004) found that transient vibrations are more uncomfortable than steady state vibrations of a similar magnitude. These results imply that humans are likely quite sensitive to wander vibration.

Citing results from several previous studies, Griffin (2007) states that vibrations at the floor of a vehicle can be quite different from those at the seat and those experienced by vehicle occupants and care is needed when deciding where to place measurement transducers. Based on the known low-frequency nature of wander, and the results presented in the literature, it is reasonable to pursue measuring acceleration on the passenger's body in addition to locations on the seat assembly. Measuring acceleration at various locations on the vehicle frame and vehicle body is not supported by these literature findings.

Griffin (2007) presents a discussion regarding the differences between measuring, evaluating and assessing vibration, explaining that measurement involves employing a physical transducer, evaluation involves calculating values to represent the relative severity of the measured vibration, and that assessment (which can be performed without measurement and evaluation) involves making judgments about the vibration. The study concludes that measurement and evaluation of vibration alone will not usually properly predict human responses that are influenced by physical factors that are not measured (e.g., environmental factors, emotional state of the subject, perceived source of vibration), and that competent measurement and evaluation supplemented by sound assessment forms the most desirable and comprehensive vibration evaluation system. With respect to the current studies, this implies that the development of a wander evaluation system will likely need to include a mechanism for human input. Further, Gillespie and Sayers (1981) say that vehicle vibrations are generally thought to be broad-band random vibrations – that is, they are not characterized by discrete frequencies, but instead occur over a range of frequencies. Because of this, it is difficult to exactly characterize vehicle vibrations and it is common to use average properties. This implies that measurements of wander will likely not be repeatable, and given the various dependencies and sources of error, it may prove difficult to develop a standard method for quantifying wander.

CHAPTER 3: EXPERIMENTAL SETUP & TEST PROCEDURES

3.1 Vehicle

As pictured in Figure 3-1, a 2000 GMC Safari cargo van owned by CDOT and known to experience wander was used in this study. CDOT personnel drove the van and a single passenger accompanied the driver to perform the data collection. The specifics of the van and tires are summarized in Table 3-A. To the authors' best knowledge, the van, including its suspension system, was in good mechanical repair and the tires were properly inflated.

Table 3-A. Characteristics of the 2000 GMC Safari cargo van employed during field measurements of vehicle wander

Characteristic	Value
Gross Vehicle Weight	2,540kg (5,600lb)
Wheelbase	2.82m (9.25ft)
Track Width	1.65m (5.41ft)
Drive	AWD
Tire Type	Uniroyal Laredo
Tire Size	P215/75 R-15

Figure 3-1. The 2000 GMC Safari cargo van employed during field measurements of vehicle wander

3.2 Roadway

Field measurements of vehicle wander were carried out on a 4.8km (3.0mi) stretch of I-70 between E-470 and SH 36 Airport Road constructed in the early 1990's and textured according to the current specification (hereafter referred to as the I-70/E-470 site). Data was collected during traverses over both the east- and west-bound alignments between mile markers 289 and 292. The PCC pavement at this location features longitudinal tining and the CDOT van was known to squirm in this area. Figure 3-2 shows the I-70/E-470 site and Figure 3-3 details the tire tread and the tining encountered.

During testing the roadway was dry and free of major debris. Some smaller debris such as sand was present, but was deemed to be normal and did not interfere with testing. The researchers did not identify any bumps along the stretch of road tested - the roadway was free of potholes and major cracking. Traffic was sufficiently light such that it did not interfere with testing at various speeds (discussed later) or compromise the safety of the testing personnel. There was very minimal wind observed throughout testing.

Figure 3-2. The I-70/E-470 testing site

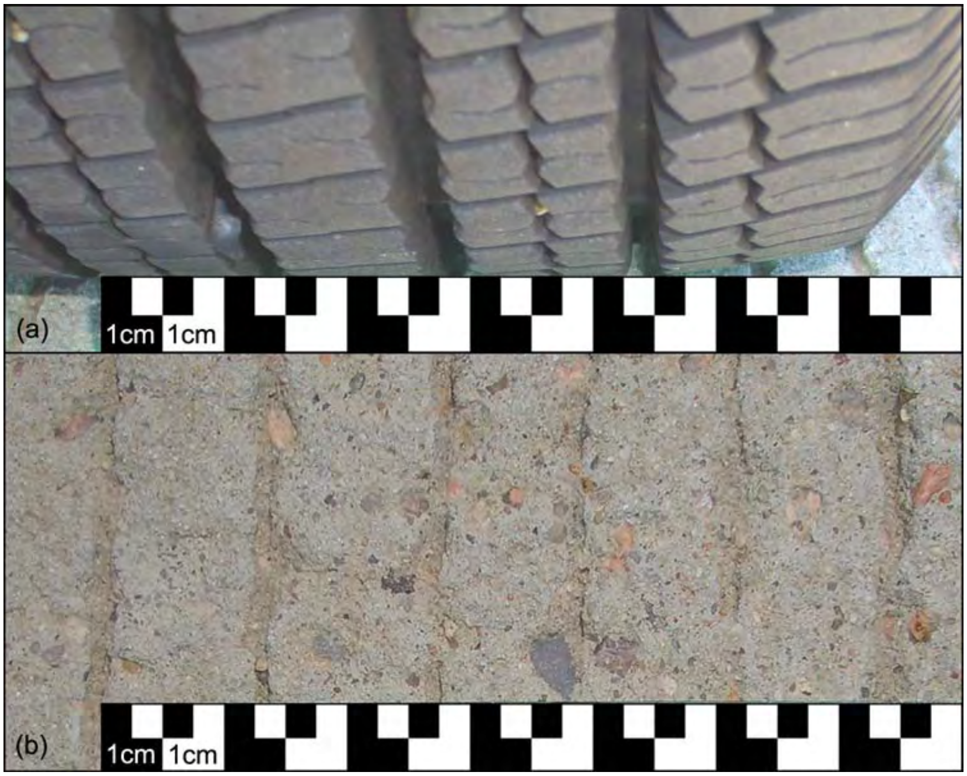

Figure 3-3. The (a) tire tread on the Uniroyal Laredo van tire and (b) longitudinal tining at the I-70/E-470 site

3.3 Sensing System

Vehicle and vehicle occupant vibrations were measured with analog ceramic piezoelectric accelerometers. The sensors are uniaxial and have a range of ±49m/s^2 (±5g), a nominal sensitivity of 100mV/m/s^2 (1V/g), and a nominal resonant frequency of 3,000Hz. The manufacturer stated frequency range (±5% accuracy) is 0.06-450Hz – sufficient to capture the recommended range of 0.5-80Hz for measuring vehicle vibrations. In addition, the sensors are sufficiently accurate to capture the low-amplitude vibrations associated with wander, with a resolution of 3x10^{-5}m/s^2 (3x10^{-6}g) and less than 1% and 5% nonlinearity and transverse sensitivity, respectively.

The accelerometer data was collected with a 16-bit, 200kHz data acquisition system (DAQ). Each channel (i.e., accelerometer) was sampled at 2000Hz and before being digitized, the analog data was low pass filtered with 3-pole Butterworth low pass filter with a -3dB cut-off frequency of 500Hz (i.e., anti-aliasing filtering). This combination of sampling frequency, anti-aliasing filtering and sensor characteristics ensures that the digital data is accurate and well resolved from less than 1Hz to 450Hz and that the data is not contaminated with higher frequency noise. The noise present in the sensing system (i.e., accelerometers, DAQ and cabling) was about 0.002m/s^2 (0.2mg).

3.4 Test Procedures

3.4.1 Day One

Field testing was first conducted on November 19, 2008. Lateral (perpendicular to the forward travel of the vehicle) acceleration data was collected from two different accelerometers during each test pass, and several different accelerometer placements were tested. The first accelerometer was fixed to the seat frame and oriented to measure lateral acceleration, perpendicular to the direction of forward vehicle travel (Figure 3-4a). This accelerometer placement was the same for all test runs and provided data similar to that collected in the 2006 preliminary study. The location of the second accelerometer varied based on the results of the literature review (see Chapter 2). Locations included two positions on the seat itself: the seat back (Figure 3-4b) and the seat cushion (Figure 3-4c). These locations were chosen because of their specification in ISO-2631, because the seat assembly has low pass filter characteristics, and because vibrations enter the passenger’s body through the seat (see Corbridge and Griffin, 1986; Nishiyama et al., 2000). The other location tested was the passenger’s head (Figure 3-4d). This placement was chosen because of the human body’s tendencies to amplify low frequencies and attenuate high frequencies and because it is the vibration experienced by vehicle occupants (in contrast to vehicle vibrations) that gives rise to the negative feedback. In each of these cases, the sensor was oriented to measure lateral acceleration.

During testing, the position of the seat assembly was not modified. The vehicle occupant tried to maintain similar posture during and between test runs. The literature indicates that posture can have a strong affect of the transmission of vibration from the seat to vehicle occupants and on the

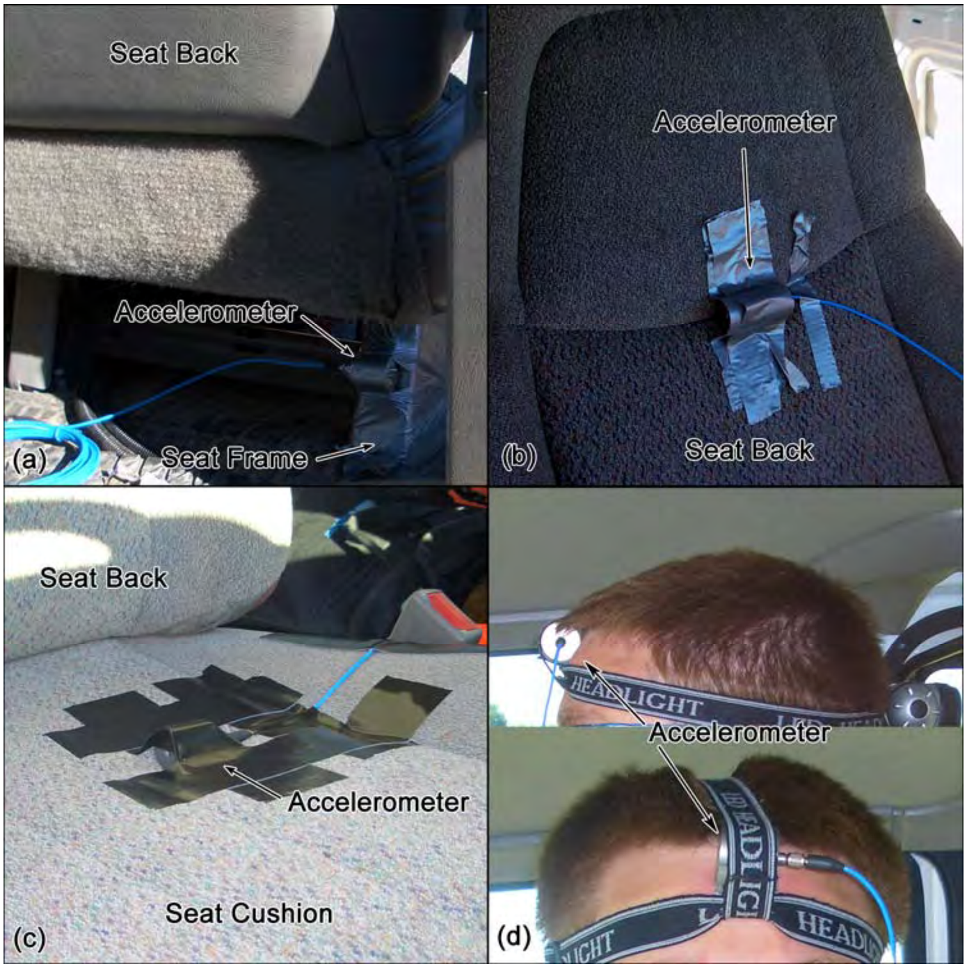

Figure 3-4. Accelerometers placed on the (a) seat frame, (b) seat back, (c) seat cushion, and (d) passenger's head

vibration response of the vehicle occupants themselves (e.g., Paddan and Griffin, 1994; Lewis and Griffin, 1996).

Data was collected with the van traveling at constant velocity in the right hand lane. Table 3-B summarizes the test runs. A hand-held, push-button trigger was used to record locations where wander was observed. The trigger is an important component of the sensing system since there are several sources of acceleration similar to wander. As will be discussed in more detail later, human input is valuable when trying to identify and characterize wander vibrations.

Table 3-B. Summary of day one test runs

Run	Direction	Speed km/h (mph)	Accelerometer Location
1-1	East	113 (70)	Seat Frame, Seat Cushion
1-2	West	113 (70)	Seat Frame, Seat Cushion
1-3	East	97 (60)	Seat Frame, Seat Cushion
1-4	West	97 (60)	Seat Frame, Seat Cushion
1-5	East	80 (50)	Seat Frame, Seat Cushion
1-6	West	80 (50)	Seat Frame, Seat Cushion
1-7	East	113 (70)	Seat Frame, Passenger's Head
1-8	West	113 (70)	Seat Frame, Passenger's Head
1-9	East	97 (60)	Seat Frame, Passenger's Head
1-10	West	97 (60)	Seat Frame, Passenger's Head
1-11	East	80 (50)	Seat Frame, Passenger's Head
1-12[1]	West	80 (50)	Seat Frame, Passenger's Head
1-13	East	113 (70)	Seat Frame, Seat Back
1-14	West	113 (70)	Seat Frame, Seat Back
1-15	East	97 (60)	Seat Frame, Seat Back
1-16	West	97 (60)	Seat Frame, Seat Back
1-17	East	80 (50)	Seat Frame, Seat Back
1-18	West	80 (50)	Seat Frame, Seat Back

[1] data not available due to equipment malfunction

3.4.1 Day Two

A second round of field testing was conducted on July 1, 2009. Lateral acceleration data was collected from two different accelerometers during each test pass. The first accelerometer was fixed to the seat cushion (as specified in ISO-2631, see Figure 3-4c), and the second accelerometer was fixed to the passenger's head (Figure 3-4d). These testing locations were chosen based on analysis of field data collected on November 11, 2008 and based on a desire to perform analysis per ISO-2631.

The objectives of the second round of field testing were to collect data to enable repeatability analysis and to allow for analysis per ISO-2631. Table 3-C summarizes the test runs. As before, data was collected with the van traveling at constant velocity in the right hand lane. Several improvements to the data collection process were implemented for the second round of testing. First, the van driver paid particular attention to maintaining as consistent of a vehicle track as possible. Second, the vehicle occupant used different trigger techniques (e.g., off vs. constantly on vs. pulsing) to differentiate between no, low, and high-severity wander. Third, consistent start and stop points were marked with the trigger to enable data from different passes to be aligned for comparison. It is worth noting that the test subject varied between day one and day two. While both subject were male and in good physical condition, the height and weight of the day one and day two subjects were 6’1”, 175lb and 5’10”, 175lb, respectively. The subjects maintained similar posture, and these differences are only expected to have minor influences on the measurement of acceleration on the subject’s head.

Table 3-C. Summary of day two test runs

Run	Direction	Speed km/h (mph)	Accelerometer Location
2-1	East	113 (70)	Seat Cushion, Passenger's Head
2-2	West	97 (60)	Seat Cushion, Passenger's Head
2-3	East	113 (70)	Seat Cushion, Passenger's Head
2-4	West	113 (70)	Seat Cushion, Passenger's Head
2-5	East	97 (60)	Seat Cushion, Passenger's Head
2-6	West	113 (70)	Seat Cushion, Passenger's Head
2-7	East	97 (60)	Seat Cushion, Passenger's Head
2-8	West	80 (50)	Seat Cushion, Passenger's Head
2-9	East	113 (70)	Seat Cushion, Passenger's Head
2-10	West	113 (70)	Seat Cushion, Passenger's Head
2-11	East	80 (50)	Seat Cushion, Passenger's Head
2-12	West	113 (70)	Seat Cushion, Passenger's Head
2-13	East	113 (70)	Seat Cushion, Passenger's Head
2-14	West	113 (70)	Seat Cushion, Passenger's Head
2-15	East	80 (50)	Seat Cushion, Passenger's Head
2-16	West	113 (70)	Seat Cushion, Passenger's Head
2-17	East	113 (70)	Seat Cushion, Passenger's Head
2-18	West	113 (70)	Seat Cushion, Passenger's Head
2-19	East	113 (70)	Seat Cushion, Passenger's Head
2-20	West	80 (50)	Seat Cushion, Passenger's Head
2-21	East	80 (50)	Seat Cushion, Passenger's Head
2-22	West	113 (70)	Seat Cushion, Passenger's Head
2-23	East	113 (70)	Seat Cushion, Passenger's Head
2-24	West	113 (70)	Seat Cushion, Passenger's Head
2-25	East	80 (50)	Seat Cushion, Passenger's Head
2-26	West	113 (70)	Seat Cushion, Passenger's Head
2-27	East	113 (70)	Seat Cushion, Passenger's Head
2-28	West	113 (70)	Seat Cushion, Passenger's Head
2-29	East	113 (70)	Seat Cushion, Passenger's Head
2-30	West	113 (70)	Seat Cushion, Passenger's Head
2-31	East	113 (70)	Seat Cushion, Passenger's Head
2-32	West	80 (50)	Seat Cushion, Passenger's Head

CHAPTER 4: RESULTS

4.1 Characteristics of Acceleration Due to Wander

One objective of this study was to characterize vibrations due to vehicle wander (wander). A vehicle traveling at highway speeds vibrates laterally due to a number of excitation sources, e.g., engine, rotation of the tires, road roughness, pavement bumps and joints, wind, and wander. Most of these excitation sources create lateral vehicle vibration on the same order of magnitude or greater than that due to wander. Further, some sources result in vibration in the same frequency range as wander, e.g., wind, bumps. The location of the sensor (accelerometer) has a significant effect on which of these sources of lateral vibration are measured. From top to bottom, Figure 4-1 presents raw lateral acceleration measured at the passenger’s head, seat frame, seat cushion, and seat back. Plots on the left in Figure 4-1 show data from stretches where wander was not observed, while those on the right show data where wander was observed. The 4.5 seconds of data shown in each plot corresponds to about 122m (400ft) of vehicle travel.

As shown in Figure 4-1, depending on the sensor location, there can be little visually discernable difference between the raw acceleration records during wander and non-wander behavior. This is particularly true for the seat frame position. The seat frame is rigidly attached to the vehicle body, and while the vehicle suspension does dampen some vibration, the low-frequency wander vibrations are masked by other, higher frequency signals (e.g., engine vibration, tire rotation). The high frequency noise that obscures wander in the seat frame measurements is somewhat attenuated by the low pass characteristics of the seat cushion and seat back (see Griffin, 2007) and limited differences are visually discernable between the wander and non-wander data sets. The high frequency noise is further attenuated by the body (and in fact, 0.5-2Hz signals may be amplified, see Paddan and Griffin, 1988, 1998), and Figure 4-1 shows clear differences between wander and non-wander behavior when acceleration is measured at the passenger’s head. For this reason, the characteristics of wander vibration will be explored using the passenger’s head measurement runs from testing day one (Runs 1-7 through 1-11). Note that Section 4.2 details the results of the studies regarding the optimal sensor location to measure wander vibrations.

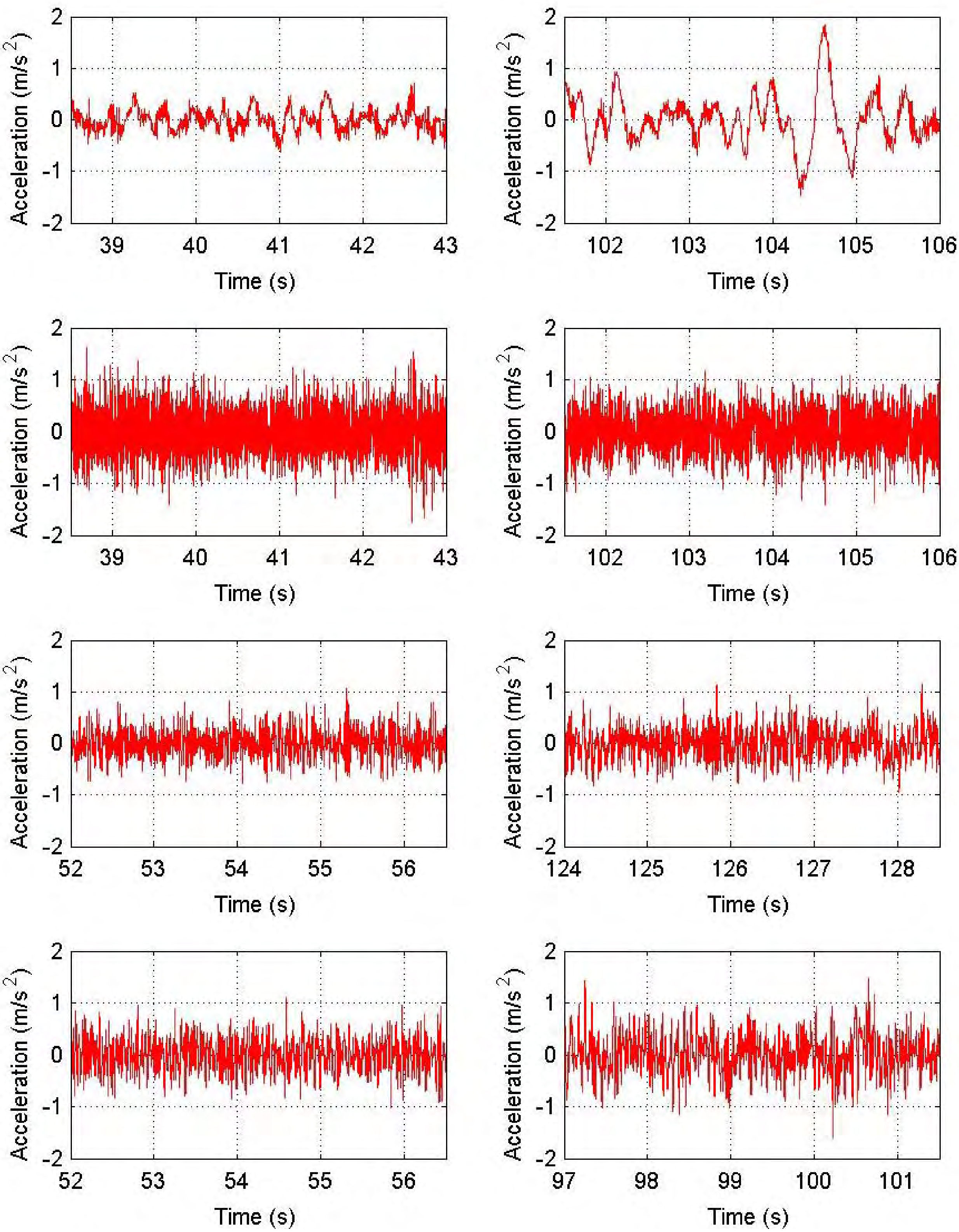

Figure 4-1. Raw lateral acceleration data measured at the passenger's head, seat frame, seat cushion and seat back (from top to bottom) with data from non-wander behavior on the left and wander behavior on the right

Frequency domain analysis was performed to determine the frequency content of each signal and to identify a characteristic frequency range where wander occurs. Spectrogram analysis is performed by computing Short Time Fourier Transforms (STFT) for adjacent or overlapping segments of a data file (i.e., stretches of road). This type of analysis, also referred to as the time-dependent Fourier Transform, is commonly used to analyze nonstationary signals (see Oppenheim and Schafer, 1999). Spectrogram analysis is useful here as it allows comparison of the frequency content of wander and non-wander stretches from the same test run. Figure 4-2b presents the spectrogram from the passenger's head acceleration from Run 1-10. The spectrogram was computed with five-second windows with one-half-second overlap between adjacent windows. To show where wander was observed; the hand trigger signal is shown (Figure 4-2a). A trigger value of zero (i.e., off) corresponds to no wander being observed and a trigger value of one (i.e., on) corresponds to wander being observed. The spectrogram in Figure 4-2 is presented in decibels (dB) and therefore a value closer to zero (darker) indicates more power than a value further from zero (lighter). Given that wander is a low-frequency phenomenon, the spectrogram is only shown for 0-10Hz.

Inspection of Figure 4-2 reveals that areas where wander is observed generally have more power in the 1-3Hz frequency band than areas where wander is not observed. For example, compare the window of time T=40-60s where the trigger indicates that wander was not observed to the T=120-140s window where the trigger indicates that wander was observed. Examining individual power spectra from non-wander and wander stretches (see Figure 4-2c, d) confirms that wander corresponds to additional power in the 1-3Hz frequency band. These results are further corroborated by Figure 4-3, which presents the total power present in the 0-5Hz band as a function of time (i.e., the integral of the power from 0-5Hz for each time window in the spectrogram). In general, areas where wander occurred exhibit higher vibration signal power than those where wander did not occur.

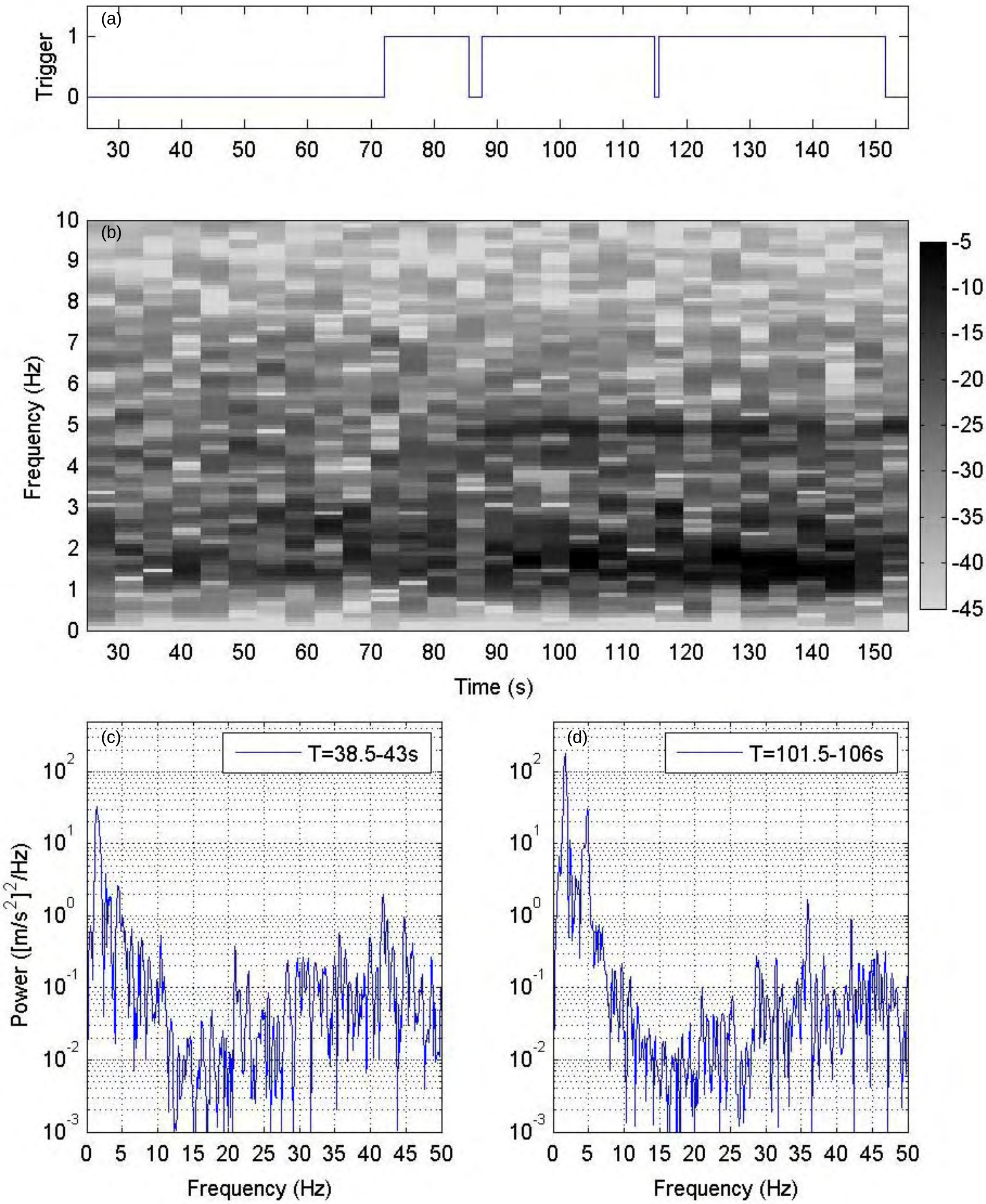

Figure 4-2. Frequency domain analysis of Run 1-10: (a) trigger, (b) spectrogram, and power spectra from (c) non-wander and (d) wander stretches

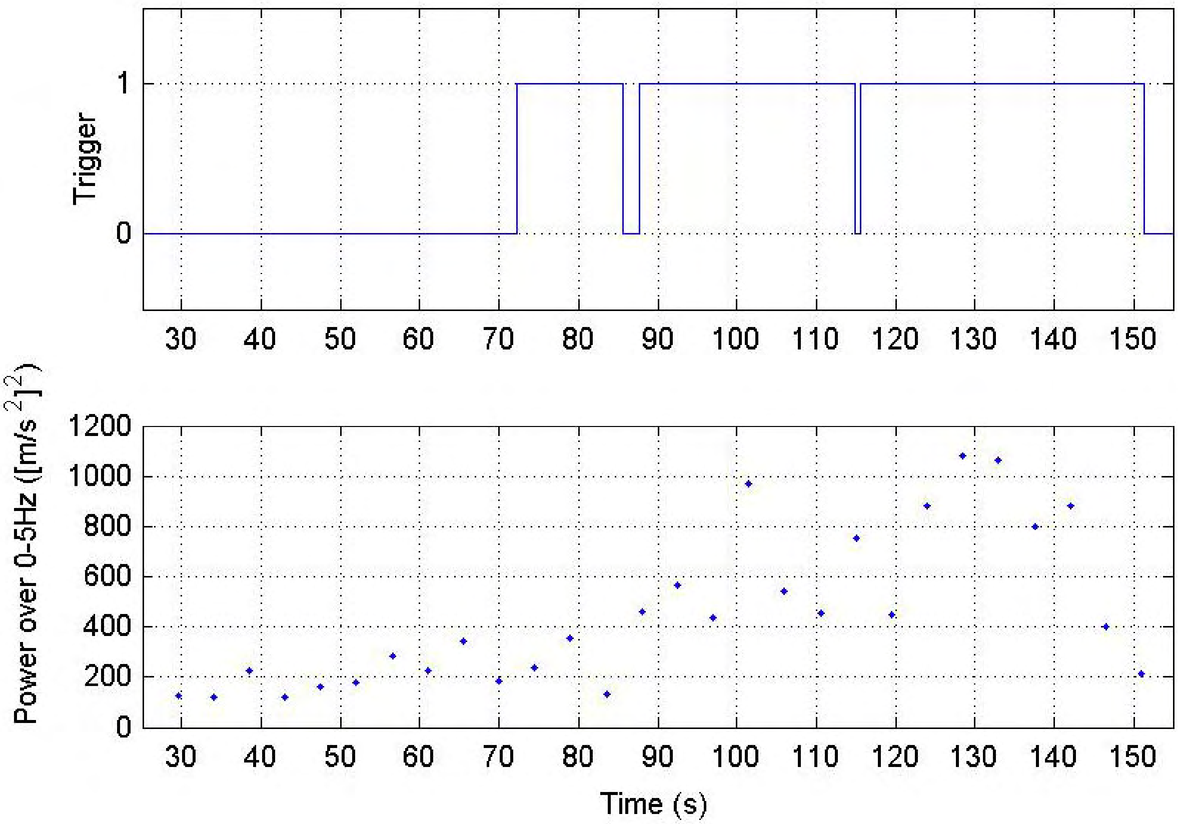

Figure 4-3. Run 1-10 trigger signal (top) and total power in the 0-5Hz band (bottom) (note that the integration time windows correspond to those used in the spectrogram)

Many of the excitation sources that cause lateral vehicle vibration are impulse-type loadings, e.g., wind, wander, pavement bumps, cracks and joints. The free vibration response of the vehicle body to impulse loading is dominated by the van's characteristics, e.g., mass, suspension stiffness, damping. Therefore, the van's response to wander, wind, pavement joints, etc., can be quite similar and difficult to separate. To explore the low-frequency accelerations believed to correspond to wander, the raw data was digitally low pass filtered. While, as discussed earlier, the body acts a low pass filter, applying a digital filter ensures that consistent comparisons can be made within a dataset and between datasets. Figure 4-4 shows the raw (red) and low pass filtered (5Hz cut-off frequency, bold blue line) lateral accelerations measured at the passenger's head during Run 1-10. For reference, the areas enclosed by the dashed green rectangles represent areas where the trigger indicated that wander was observed. Inspection of Figure 4-4 reveals that the areas where wander was observed often correspond to 1.5-3Hz waveforms that usually exceed

0.75m/s^2 (0.076g) in peak amplitude and often exceed 1m/s^2 (0.102g). In areas where wander is not observed, it is still possible to find 1.5-3Hz waveforms, but they are typically less than 0.75m/s^2 (0.076g) and likely either due to very low severity wander or other vibration sources.

Some discussion of the triggering technique used here is appropriate before further presentation of the results. By means of a push-button device, the vehicle occupant is able to indicate, or trigger, when wander is observed. However, when driving at highway speeds it is very difficult to trigger individual or isolated wander events – the process of assessing whether or not the observed vibration is wander or not (i.e., deciding whether or not to push the trigger button) is not an instantaneous process. There is a lag-time associated with triggering. This is illustrated in the time window T=82-88s in Figure 4-4. It appears that wander ceases at about T=82s, but the trigger is not released until T=85s – a delay of three seconds. Wander then resumes at T=86.5s, but the trigger is not pressed until T=88s – a delay of one and a half seconds.

Due to the difficulty of triggering individual wander events, the trigger was used to indicate larger-scale areas where wander was prevalent. Specifically, if an individual wander event was observed, but subsequent vibration was normal, the trigger was likely not pressed. This can be observed at several locations in Figure 4-4, including T = 38s and 152-154s. Conversely, if wander was prevalent in an area and therefore the trigger was pressed, but stopped for a short time (e.g., 1-2 seconds) before wander resumed, the trigger was likely not released. This can be observed at T = 95-97s and 130-131.5s in Figure 4-4.

Similar results to those discussed above are found in the time histories for Runs 1-7, 1-8, 1-9 and 1-11, shown in Figures 4-5 through 4-8, respectively. Table 4-A summarizes the mean lateral acceleration (in terms of root mean square, RMS) observed in wander zones versus that observed in non-wander zones for Runs 1-7 through 1-11. As shown, the RMS acceleration in wander zones is about 37% (0.1 m/s^2 [0.010g]) greater than that in non-wander zones. Further, there is no overlap between the non-wander and wander data – the greatest non-wander RMS acceleration (Run 1-7, 0.319 m/s^2 [0.033g]) is less than the least wander RMS acceleration (Run 1-11, 0.334 m/s^2 [0.034g]). These results show that computing the lateral RMS acceleration is a suitable way to compare wander and non-wander areas. It follows that a system to measure wander could involve calculating the RMS acceleration using a windowed approach (i.e., similar to spectrogram analysis where the STFT is computed for adjacent time windows). However, it is important to note that these vibration levels are vehicle, tire, vehicle occupant and even posture dependent. Therefore, the 0.75m/s^2 (0.076g) threshold for individual waveforms or the 0.365 m/s^2 (0.037g) threshold for RMS acceleration for a given time window found here cannot be considered as a criteria to determine wander. Further, as mentioned previously, there are a number of vibration sources in addition to wander that could result in similar increase in RMS acceleration. This highlights the importance of having human input when trying to measure or assess wander vibration. These findings and observations are in line with what other researchers have found when developing systems to assess discomfort due to vibration – namely that human input remains necessary, even if sophisticated measurement techniques are employed. (e.g., Gillespie and Sayers, 1981; Griffin, 2007).

Table 4-A. RMS lateral accelerations from non-wander and wander zones from Runs 1-7 through 1-11 (accelerometer on passenger's head)

Run	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)
1-7	0.319	0.386
1-8	0.235	0.374
1-9	0.270	0.353
1-10	0.247	0.378
1-11	0.261	0.334
Mean	**0.266**	**0.365**

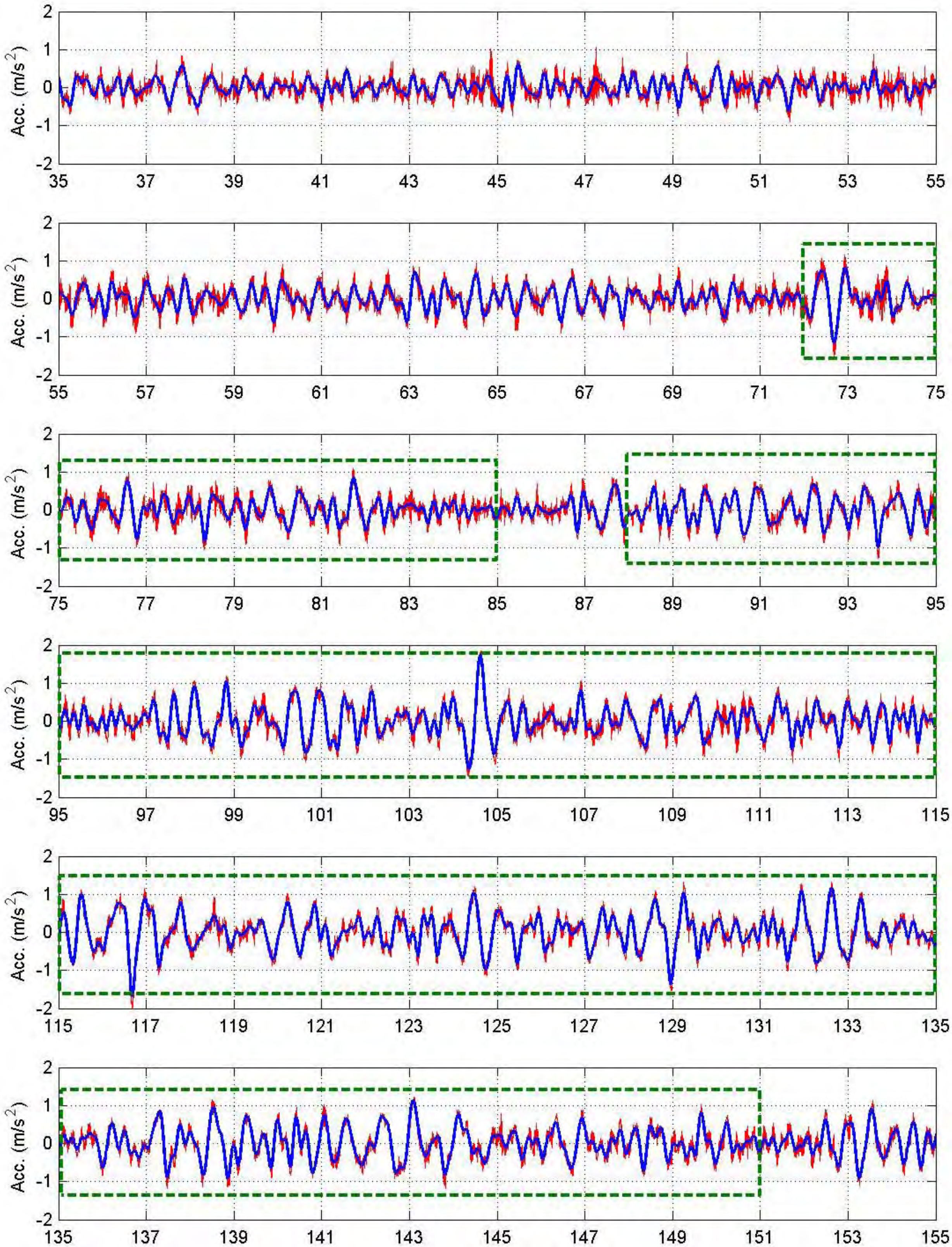

Figure 4-4. Raw (red) and low pass filtered (5 Hz cut-off frequency) (blue) lateral acceleration data from Run 1-10. Hatched areas indicate where wander was prevalent according to the hand trigger.

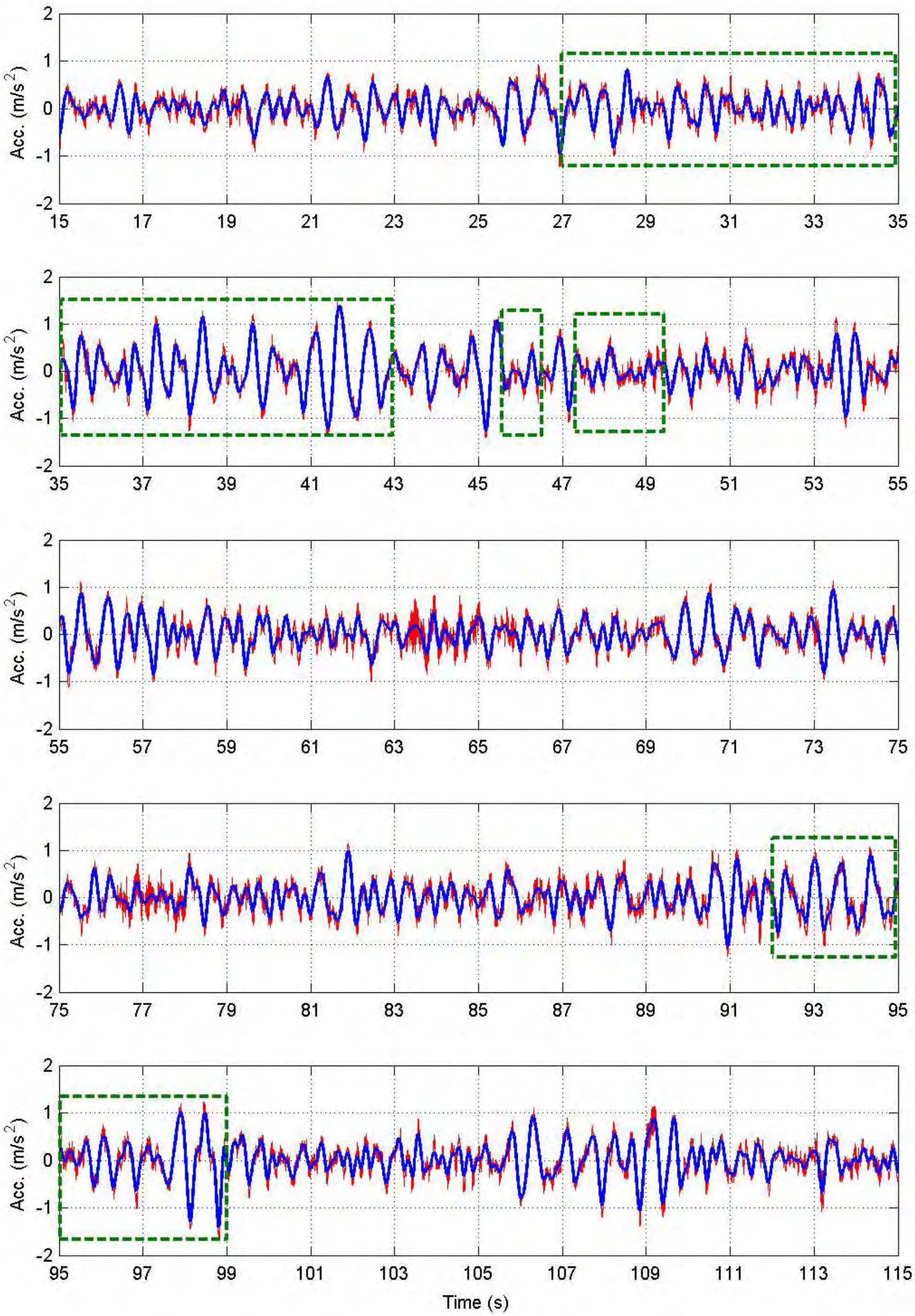

Figure 4-5. Raw and low pass filtered (5 Hz cut-off frequency) lateral acceleration data from Run 1-7

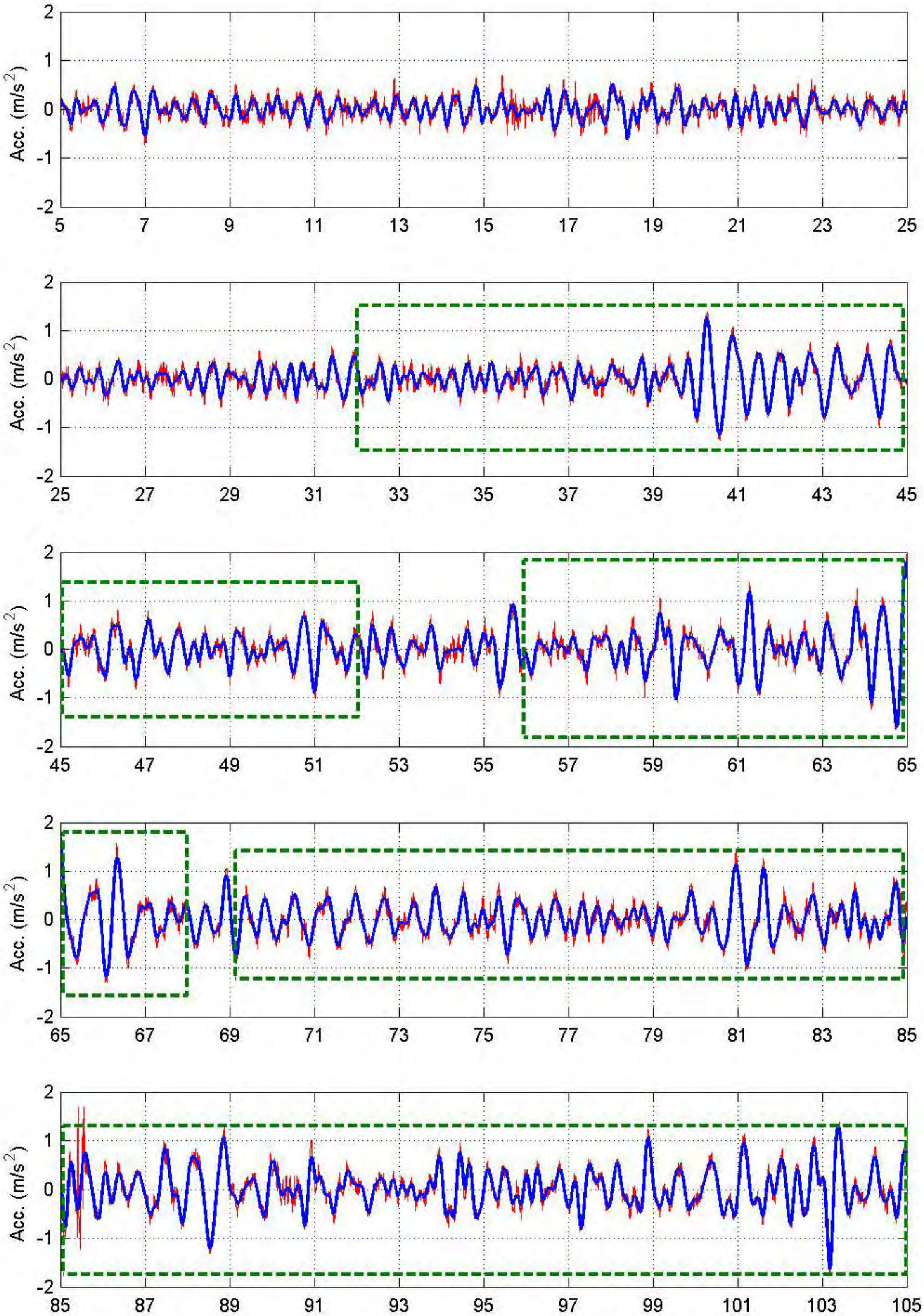

Figure 4-6. Raw and low pass filtered (5 Hz cut-off frequency) lateral acceleration data from Run 1-8

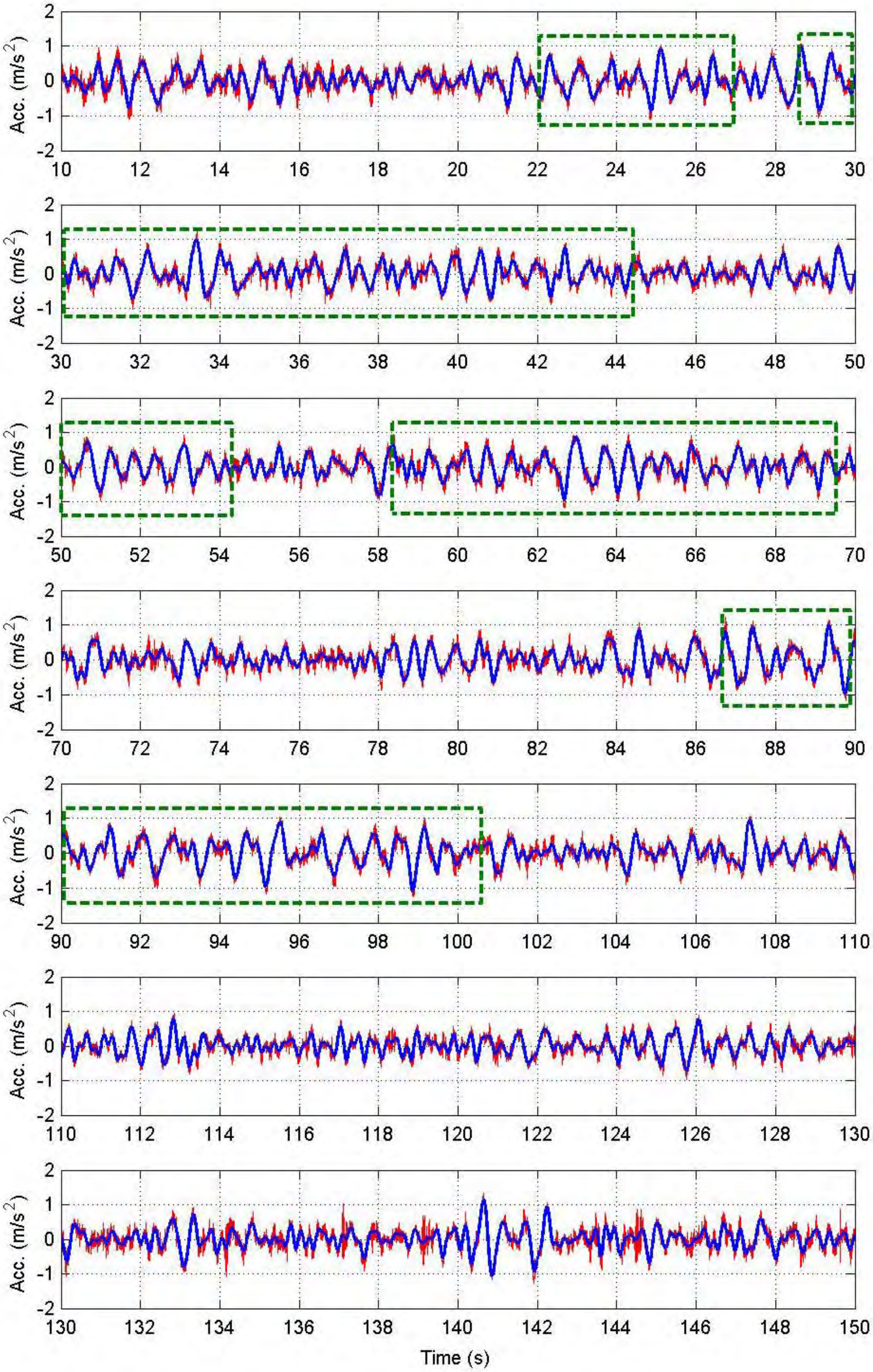

Figure 4-7. Raw and low pass filtered (5 Hz cut-off frequency) lateral acceleration data from Run 1-9

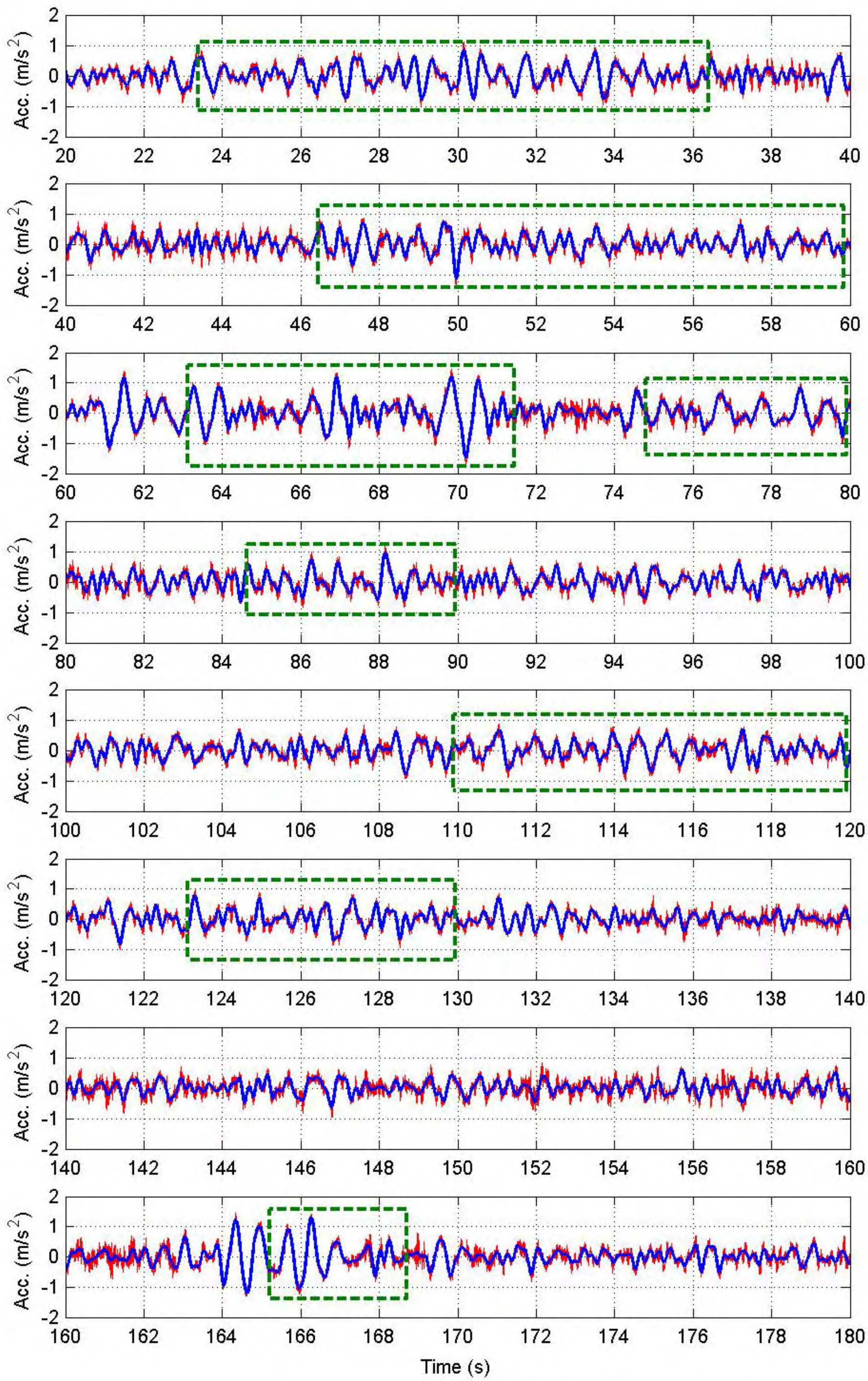

Figure 4-8. Raw and low pass filtered (5 Hz cut-off frequency) lateral acceleration data from Run 1-11

Further analysis was performed with data collected during the second round of field testing, where an attempt was made to quantify wander into two distinct levels, low and high. Figure 4-9 shows the acceleration time history from Run 2-13, where low- and high-severity wander are indicated in green and red boxes, respectively. The low- and high-severity zones are visually discernable, with the high-severity zones having a higher concentration of waveforms in excess of $1 m/s^2$. However, as expected inspection reveals that the low-severity wander zones contain isolated instances of high-severity wander, and vice versa. This corroborates the current understanding that wander is due to individual, constantly changing interactions between the tires and the tread (see section 2.1). Given small scale variations in the tining pattern and complicated tire tread designs, wander is a transient, stochastic phenomenon – it is expected that trends can be discerned through larger scale averaging, but examination of individual events may appear random. Table 4-B summarizes the RMS levels from all the 113km/h runs (both east- and west-bound) from day two. The results indicate that on average, low- and high-severity wander consist of RMS accelerations of 0.297 and 0.349 m/s^2, respectively, representing 16% and 37%

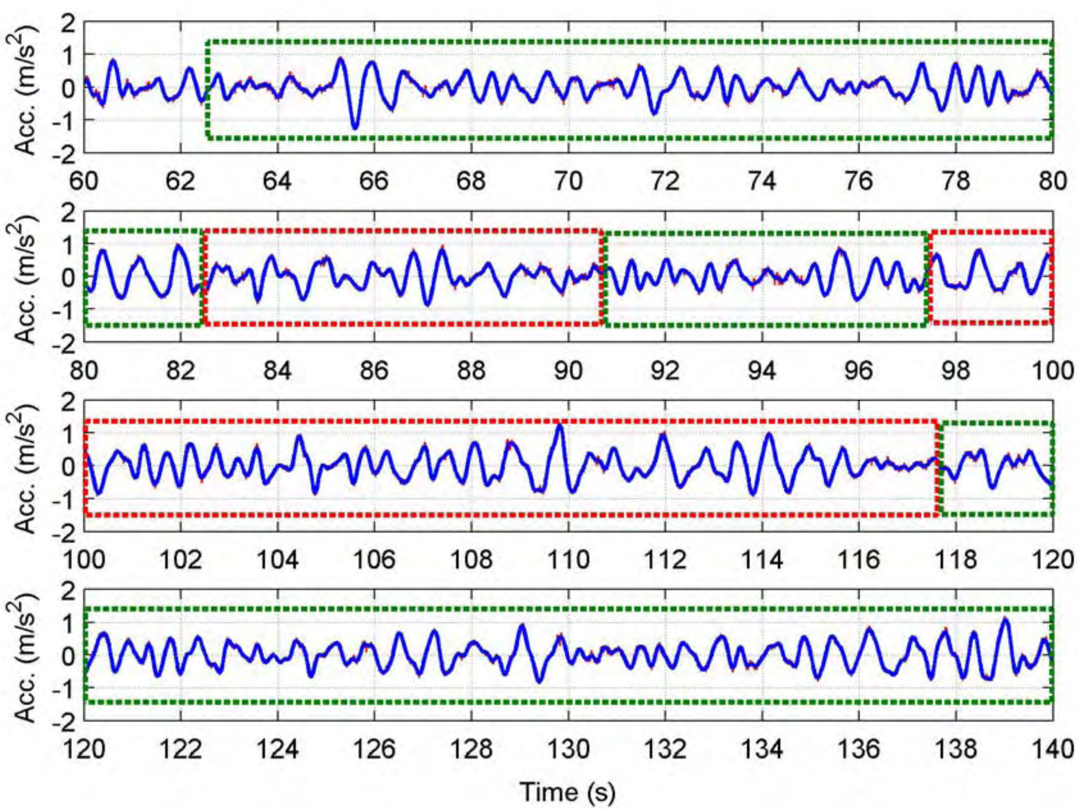

Figure 4-9. Raw and low pass filtered (5 Hz cut-off frequency) lateral acceleration data from Run 2-13

increases from no wander vibration levels, respectively. While these results are in agreement with day one results presented earlier, some small differences in acceleration levels are expected due to different vehicle occupants (see section 3.4.2).

Table 4-B. RMS lateral accelerations from no, low and high-severity wander zones from testing day 2 runs (accelerometer on passenger's head, v=113km/h)

Run	RMS Acc. from No Wander Zones (m/s^2)	RMS Acc. from Low Wander Zones (m/s^2)	RMS Acc. from High Wander Zones (m/s^2)
2-1	0.272	0.295	0.365
2-3	0.245	0.260	0.289
2-4	0.229	0.243	-
2-6	0.177	0.251	0.354
2-9	0.333	0.284	0.394
2-10	0.206	0.267	0.347
2-12	0.267	0.290	0.345
2-13	0.322	0.322	0.371
2-14	0.289	0.269	-
2-16	0.221	0.298	0.282
2-17	0.349	0.353	0.401
2-18	0.235	0.324	0.466
2-19	0.344	0.315	0.337
2-22	0.183	0.275	0.273
2-23	0.284	0.322	0.321
2-24	-	0.312	0.372
2-26	0.218	0.253	0.333
2-27	0.219	0.305	0.336
2-28	0.248	0.271	-
2-29	-	0.411	0.351
2-30	0.213	0.276	-
2-31	-	0.344	0.354
Mean	**0.255**	**0.297**	**0.349**

4.2 Influence of Accelerometer Location

Another objective of this research was to identify the optimal accelerometer placement to capture vehicle wander. As described in Section 3.4, four different accelerometer placements were evaluated: seat frame, seat cushion, seat back, and passenger's head. Frequency and time domain analyses were used to evaluate each placement. Spectrograms (see Figure 4-2 above) allow visualization of the frequency content of the measured acceleration in a moving time window fashion. Comparing spectra of wander and non-wander zones via spectrograms allows for the sensitivity of each placement to be evaluated. Further, computing the total power in the 0-5 Hz frequency band (see Figure 4-3 above) allows further insight into the sensitivity of each placement to the low-frequency wander vibrations. Figures 4-10 through 4-13 present the frequency domain analysis for the seat frame, seat cushion, seat back and passenger's head placements, respectively. The frequency domain analysis reveals that the passenger's head placement is the most sensitive to wander vibrations.

In the time domain, comparing RMS acceleration values for wander and non-wander zones allows the sensitivity of each placement to be further quantified, and also allows for the variability of each placement to be quantified. Tables 4-C through 4-F summarize the changes in lateral RMS acceleration from non-wander stretches (indicated by trigger=0) to wander stretches (indicated by trigger=1). The non-filtered data illustrate the difficulty in discerning wander among all the other sources of vibration and serves to underscore the necessity of filtering the data. When looking at the results for filtered data, the seat frame and passenger's head placements have the highest average increases in RMS acceleration from non-wander areas to wander areas. However, the passenger's head placement has the lowest variation across all runs (as measured by the coefficient of variation, C_v=standard deviation/mean). The remaining placements (seat cushion and seat back) have both lower RMS increases and higher levels of variation (C_v). The time domain analysis results confirm that the best accelerometer placement to measure vibration due to wander is the passenger's head.

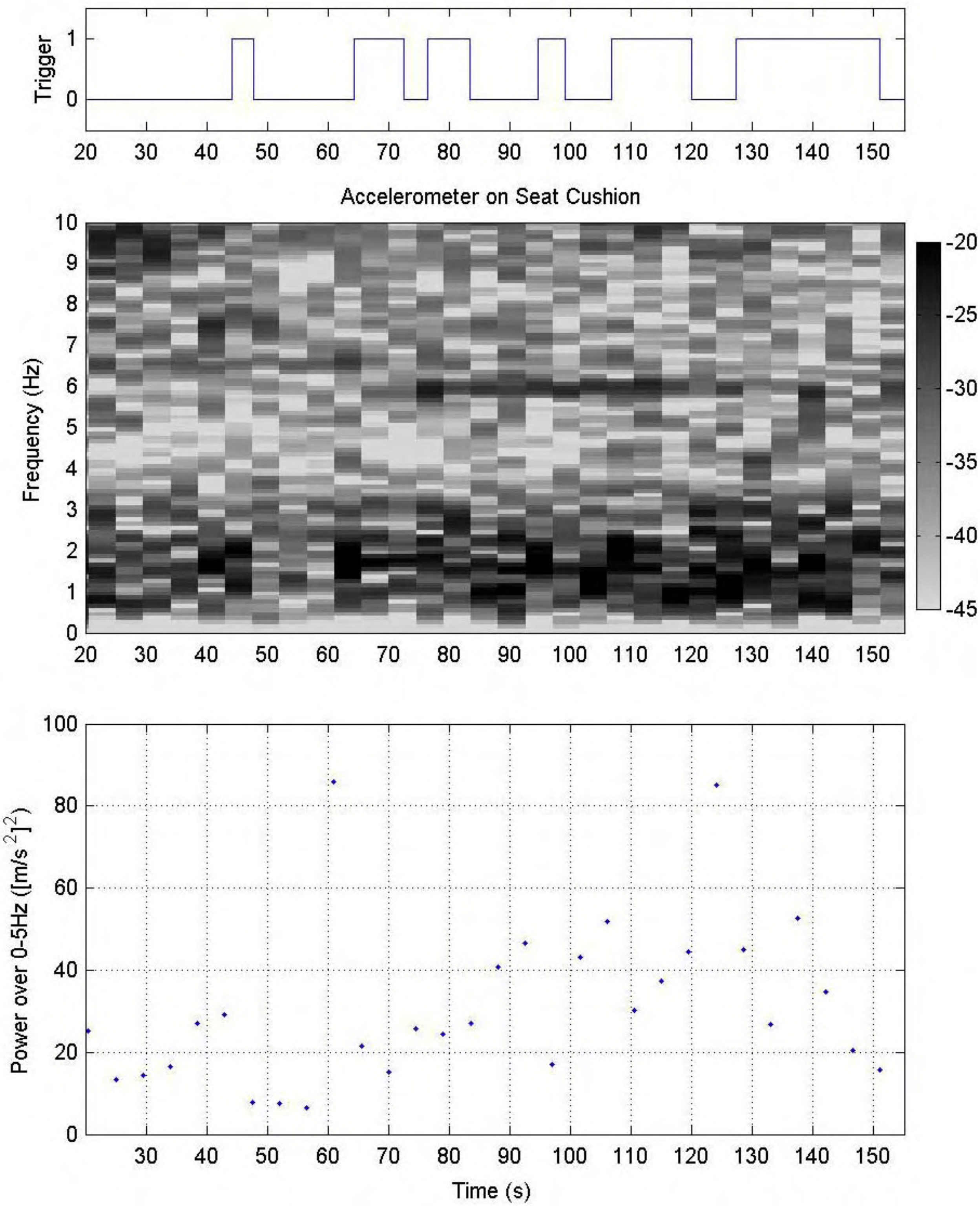

Figure 4-11. Frequency domain analysis of the seat cushion placement (Run 1-3)

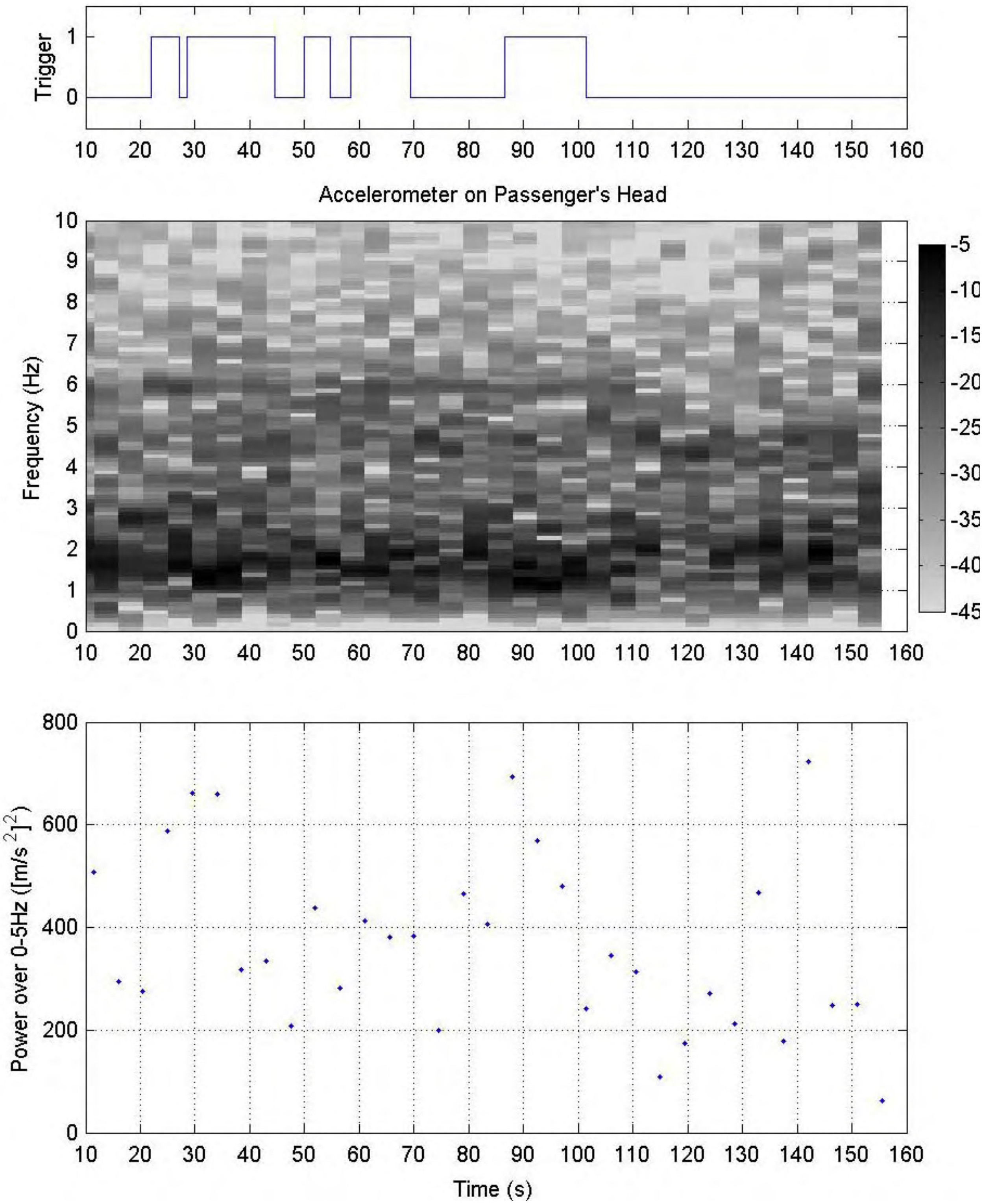

Figure 4-13. Frequency domain analysis of the passenger's head placement (Run 1-9)

Table 4-C. Summary of lateral RMS acceleration changes from non-wander to wander stretches: accelerometer on seat frame

	Unfiltered			Filtered		
Run	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change
1-1	0.495	0.470	-5%	0.055	0.074	35%
1-2	0.461	0.415	-10%	0.053	0.058	9%
1-3	0.469	0.425	-9%	0.057	0.067	18%
1-4	0.428	0.387	-10%	0.047	0.059	26%
1-5	0.383	0.328	-14%	0.045	0.069	53%
1-6	0.321	0.269	-16%	0.045	0.056	24%
1-7	0.440	0.425	-3%	0.051	0.060	18%
1-8	0.507	0.428	-16%	0.044	0.068	55%
1-9	0.446	0.399	-11%	0.047	0.049	4%
1-10	0.397	0.333	-16%	0.040	0.065	63%
1-11	0.331	0.295	-11%	0.046	0.051	11%
1-13	0.501	0.451	-10%	0.046	0.071	54%
1-14	0.474	0.402	-15%	0.045	0.059	31%
1-15	0.530	0.431	-19%	0.038	0.073	92%
1-16	0.530	0.394	-26%	0.042	0.052	24%
1-17	0.401	0.355	-11%	0.043	0.072	67%
1-18	0.369	0.280	-24%	0.037	0.050	35%
		Mean	-13%		Mean	36%
		C_v	44%		C_v	66%

Table 4-D. Summary of lateral RMS acceleration changes from non-wander to wander stretches: accelerometer on seat cushion

	Unfiltered			Filtered		
Run	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change
1-1	0.347	0.324	-7%	0.076	0.097	28%
1-2	0.361	0.317	-12%	0.081	0.082	1%
1-3	0.317	0.285	-10%	0.084	0.084	0%
1-4	0.328	0.293	-11%	0.080	0.077	-4%
1-5	0.307	0.260	-15%	0.068	0.080	18%
1-6	0.314	0.280	-11%	0.065	0.073	12%
		Mean	-11%		Mean	9%
		C_v	26%		C_v	132%

Table 4-E. Summary of lateral RMS acceleration changes from non-wander to wander stretches: accelerometer on seat back

	Unfiltered			Filtered		
Run	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change
1-13	0.479	0.460	-4%	0.078	0.096	23%
1-14	0.482	0.434	-10%	0.079	0.087	10%
1-15	0.417	0.402	-4%	0.066	0.096	45%
1-16	0.557	0.364	-35%	0.076	0.079	4%
1-17	0.406	0.384	-5%	0.063	0.089	41%
1-18	0.423	0.355	-16%	0.062	0.070	13%
		Mean	-12%		Mean	23%
		C_v	97%		C_v	75%

Table 4-F. Summary of lateral RMS acceleration changes from non-wander to wander stretches: accelerometer on passenger's head

	Unfiltered			Filtered		
Run	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change	RMS Acc. from Non-Wander Zones (m/s^2)	RMS Acc. from Wander Zones (m/s^2)	%Change
1-7	0.352	0.413	17%	0.319	0.386	21%
1-8	0.260	0.393	51%	0.235	0.374	59%
1-9	0.306	0.378	24%	0.270	0.353	31%
1-10	0.291	0.410	41%	0.247	0.378	53%
1-11	0.300	0.360	20%	0.261	0.334	28%
		Mean	31%		Mean	38%
		C_v	48%		C_v	43%

4.3 Influence of Vehicle Speed on Severity of Wander

As summarized in Table 3-B (Section 3.4), day one test runs were performed with vehicle speeds of 80, 97 and 113kmh (50, 60 and 70mph). Figures 4-14, 4-15 and 4-16 show the influence of speed on mean acceleration levels for wander and non-wander areas. The results show that speed increases vibrations in both wander and non-wander areas. Further, in most cases, the rate of increase in vibration with speed is similar between both wander and non-wander areas. Therefore, it is not possible to infer if increased speed leads to increased severity of wander, or just vibration in general. These results are supported by the qualitative observation made during testing that vehicle speed had little discernable affect on wander.

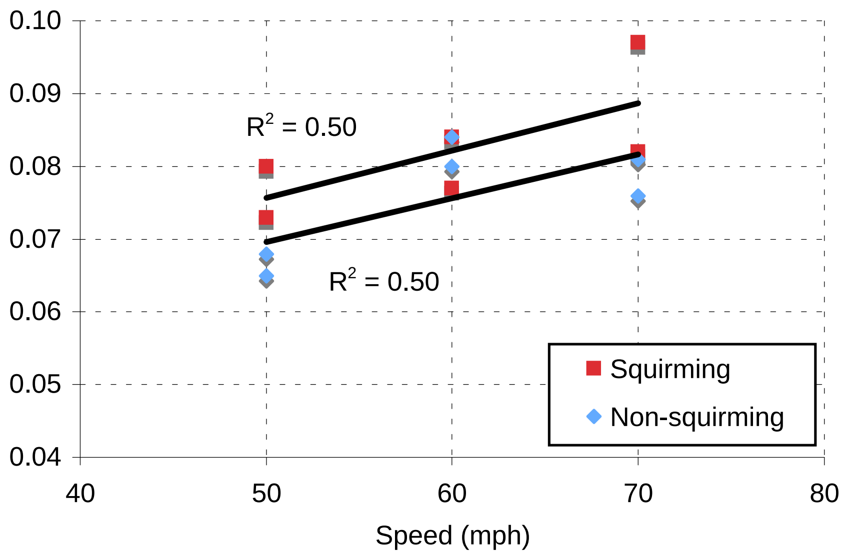

Figure 4-14. Effects of vehicle speed on seat cushion vibration

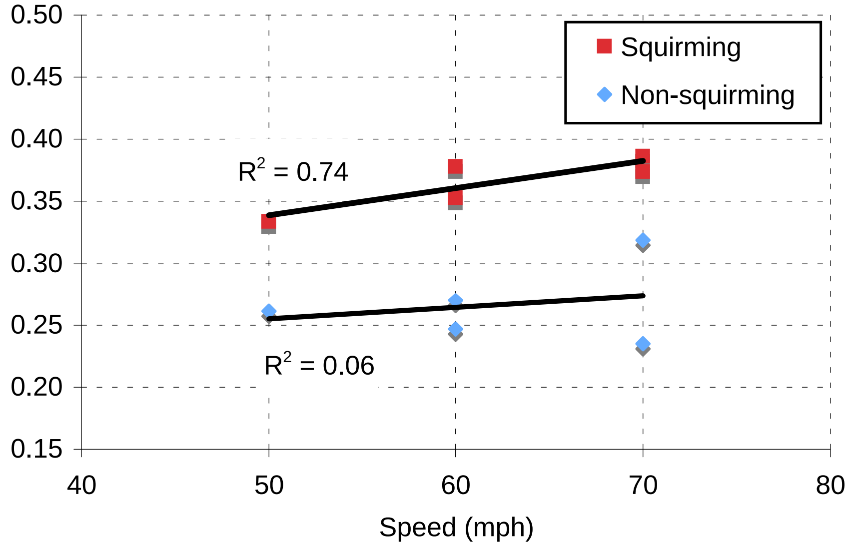

Figure 4-15. Effects of vehicle speed on head vibration

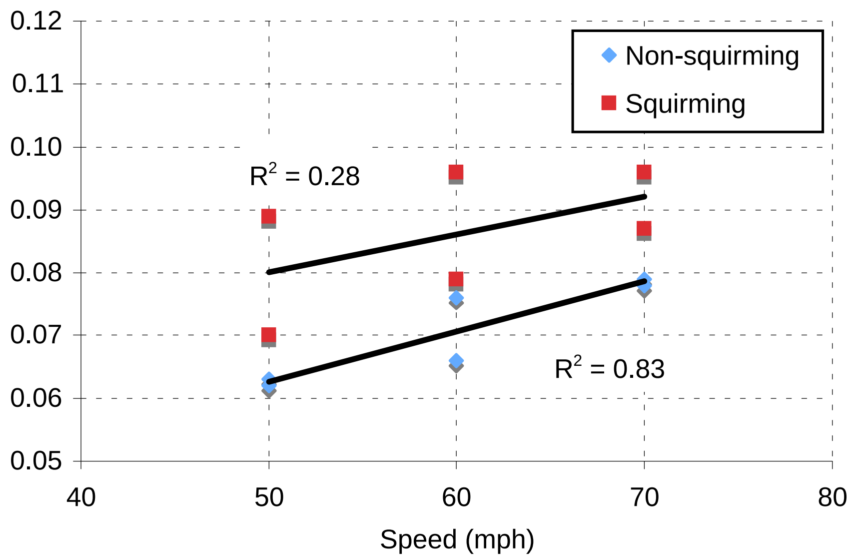

Figure 4-16. Effects of vehicle speed on seat back vibration

4.4 Repeatability

One objective of the second round of field testing was to assess the repeatability of the overall measurement system. However, based on the results of the literature review it is not reasonable to expect that wander itself will be repeatable – that is, the vibrations observed at a particular location would not be expected to be the same from run to run. Given that wander is due to interaction between tire treads and pavement grooves, even a slight lateral deviation in the driving lane will cause a change in the observed response. When driving at highway speeds, it is not possible to maintain a consistent enough course to expect wander to be repeatable. Further, as previously discussed, there are several sources of lateral vibration that make the isolation of wander behavior difficult.

In order to assess the overall measurement system's repeatability, several consecutive passes were performed over the same stretch of roadway. The van driver paid particular attention to maintaining a similar wheel track (estimated to be consistent to within 15-30cm) and the passenger marked the data files with a consistent start and stop point to allow for comparison of the different runs. Figures 4-17 and 4-18 present the trigger signals for all of the 113km/h east- and west-bound runs, respectively. Inspection reveals that there are some general consistencies between various runs, but a high level of repeatability does not emerge. For example, in the east-bound runs, the stretch of road from 250-500m is generally associated with low-severity wander and the stretch of road from 1250-1750m is generally associated with high-severity wander. These trends however, are far from precise.

The findings of the repeatability study – namely that wander is not highly repeatable, but that large scale areas exhibit similar behavior on the whole – are in line with the literature and the previous findings discussed in section 4.1. A measurement system used to study wander should include human input and studies should not attempt to identify individual wander events, but rather should look at larger scale behavior on the order of 100's of meters.

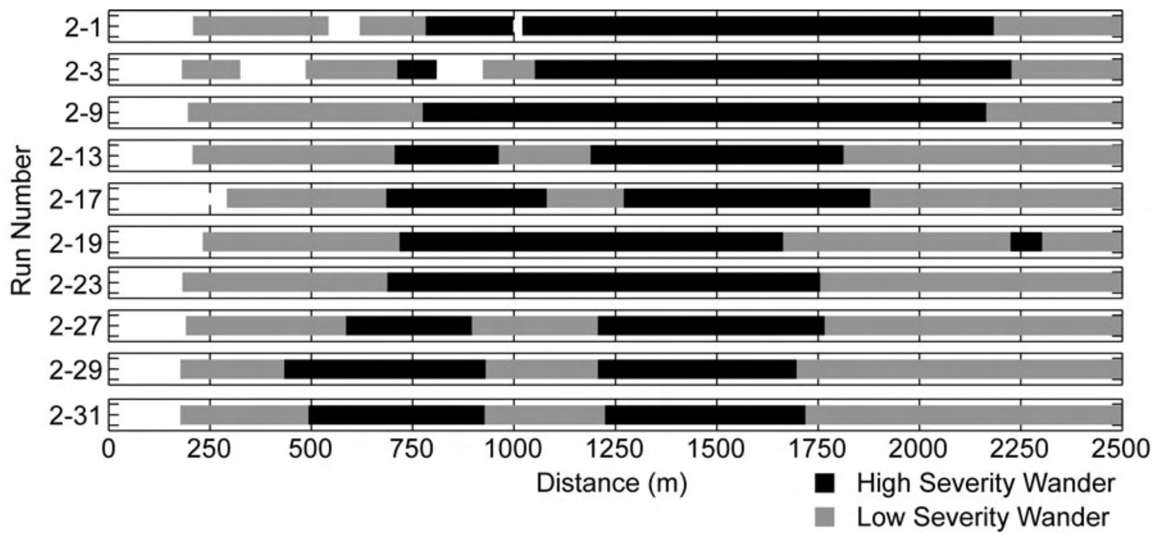

Figure 4-17. Trigger signals for 113km/h (70mph) day two east-bound runs

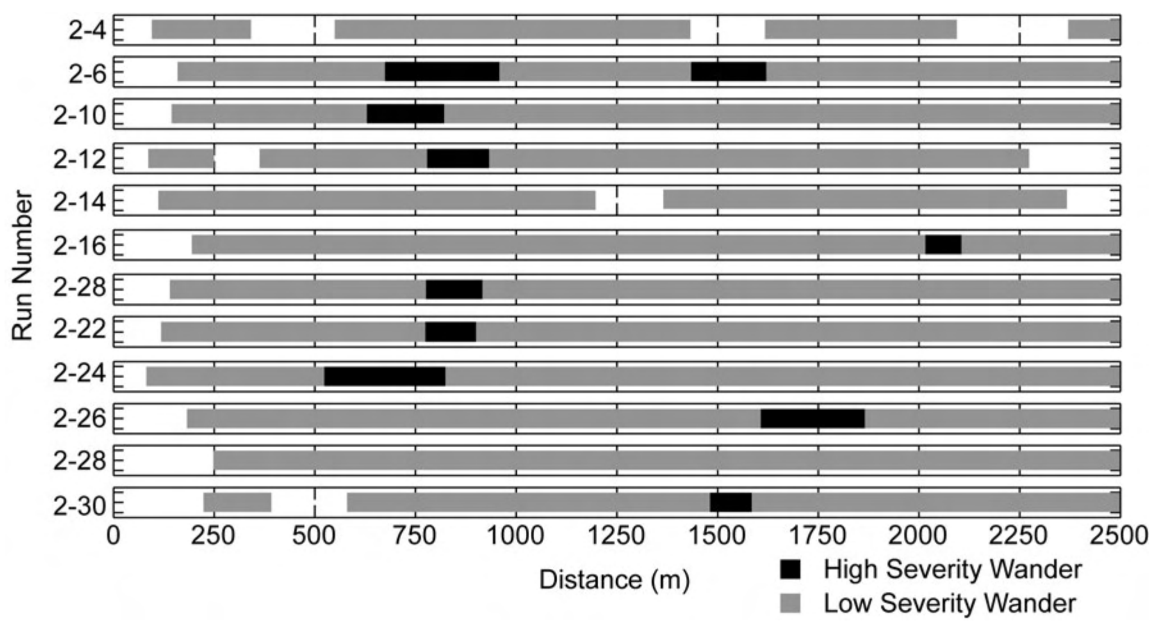

Figure 4-18. Trigger signals for 113km/h (70mph) day two west-bound runs

4.5 Analysis per ISO-2631

Published standards exist for the assessment of vehicle vibrations and the level of discomfort they may be associated with, and one objective was to evaluate if ISO standard methods could be used to identify wander. ISO analysis involves applying a very specific frequency weighting function (i.e., filter, see Figure 4.19), and for transient vibrations such as wander, computing a running RMS acceleration value. Conceptually, while the frequency weighting function of Figure 4.19 is different than the band pass filter used previously, the ISO analysis is similar to the analysis presented in section 4.1.

According to ISO-2631 several vibration measurements (e.g., seat cushion, seat back, vertical, lateral, longitudinal directions) may be combined to assess discomfort, or alternatively, a single measurement location may be used to examine a specific phenomenon (e.g., seat back *or* seat cushion). In the case of wander, it is desirable to isolate the lateral direction. Table 4-G presents the mean RMS ISO acceleration levels from no, low-, and high-severity wander zones along with

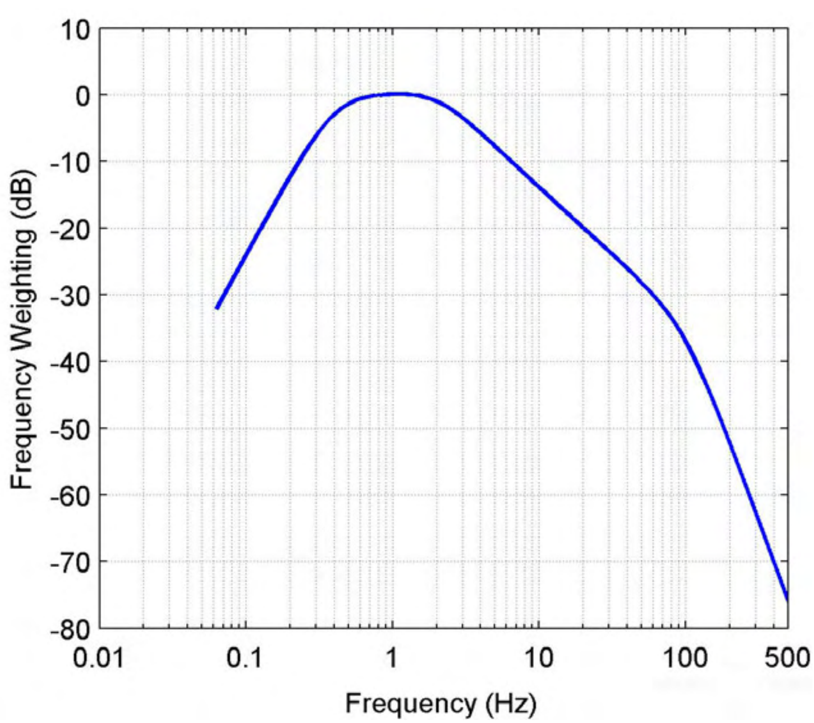

Figure 4.19. Frequency weighting function for lateral seat cushion acceleration measurements (per ISO-2631)

the percent increases from no wander zones. While on average there is a 4% and 5% increase from no wander zones to low- and high-severity wander zones, respectively, there is a significant amount of variation between the individual runs. These results are in agreement with those presented earlier in sections 4.1 and 4.2 where it was concluded that the seat cushion measurement is not as reliable as measuring acceleration on the passenger's head.

Table 4-G. Summary of lateral RMS ISO acceleration changes from no wander to low- and high-severity wander

Run	RMS ISO Acceleration from no wander zones (m/s^2)	RMS ISO Acceleration from Low wander Zones (m/s^2)	Increase from no wander zones (%)	RMS ISO Acceleration from High wander Zones (m/s^2)	Increase from no wander zones (%)
2-1	0.066	0.066	1%	0.065	-2%
2-3	0.055	0.069	26%	0.056	2%
2-4	0.064	0.057	-10%	-	-
2-6	0.036	0.060	66%	0.054	49%
2-9	0.051	0.062	22%	0.071	39%
2-10	0.060	0.059	-2%	0.068	14%
2-12	0.067	0.068	2%	0.074	10%
2-13	0.050	0.062	22%	0.066	30%
2-14	0.045	0.051	15%	-	-
2-16	0.063	0.056	-10%	0.054	-14%
2-17	0.068	0.061	-11%	0.058	-14%
2-18	0.069	0.059	-14%	0.071	2%
2-19	0.057	0.069	19%	0.063	9%
2-22	0.078	0.058	-26%	0.060	-23%
2-23	0.064	0.056	-13%	0.061	-5%
2-24	-	0.061	-	0.062	-
2-26	0.066	0.063	-3%	0.055	-17%
2-27	0.053	0.054	0%	0.054	1%
2-28	0.057	0.055	-3%	-	-
2-29	-	0.058	-	0.061	-
2-30	0.060	0.060	0%	-	-
2-31	-	0.061	-	0.063	-
		Mean	4%		5%
		C_v	487%		378%

ISO-2631 also makes recommendations for establishing levels of discomfort (see Table 4-H). Comparison of Tables 4-G and 4-H shows that even at its most severe, wander would be classified as not uncomfortable. However, as indicated in the literature, comfort is very subjective and dependent on many environmental factors. As evidenced by the negative feedback received by CDOT, and in contrast to the results of the ISO analysis, wander is perceived as uncomfortable to at least some customers.

Table 4-H. Approximate indications of human discomfort level to various magnitudes of vibration (from ISO-2631)

Vibration Magnitude[1] (m/s^2)	**Discomfort Level**
<0.315	Not uncomfortable
0.315 – 0.630	A little uncomfortable
0.500 – 1.000	Fairly uncomfortable
0.800 – 1.600	Uncomfortable
1.250 – 2.500	Very uncomfortable
>2.000	Extremely uncomfortable
[1]Vibration signals have been subjected to ISO standard methods	

CHAPTER 5: CONCLUSIONS & RECOMMENDATIONS

CDOT has received negative feedback related to the handling of vehicles driving at highway speeds over longitudinally-tined portland cement concrete pavements. The symptoms mentioned in this feedback are commonly referred to as groove wander or vehicle squirming. Using uniaxial accelerometers, lateral vehicle and vehicle occupant vibrations were monitored during several traverses of a 2000 GMC Safari cargo van over I-70 between E-470 and SH 36 Airport Road. Time domain and frequency analyses were performed to determine the vibration characteristics of wander and to determine the optimal sensor location to capture wander vibrations. The research presented herein resulted in several conclusions, as detailed below:

1) Several studies from the tire design and manufacturing community dealing with wander were identified. Wander has been discussed in the literature since the late 1960's. Early studies conducted in California concluded that the vibrations induced by wander were not hazardous. The common belief is that wander is due to an imbalance of lateral force created by individual tire tread and pavement groove contacts. The modeling of this phenomenon is becoming advanced and is taking advantage of numerical techniques. The impetus of the research studies identified was to be able to predict the severity of wander, and this is an area of ongoing research. Studies dealing with the characteristics of wander vibration and its affects on vehicle passengers were not found.

2) Much work has been done in the areas of measuring vehicle and vehicle occupant vibrations, evaluating the severity of those vibrations and to determine what levels of vibration lead to discomfort. Important findings include that the vibration measured on the floor of a vehicle can vary greatly from those measured at the seat, and that the human body tends to act as an amplifier for frequencies in the 0.5-2.5Hz band and as an attenuator for frequencies higher than 4-5Hz, with frequencies higher than 8Hz being nearly completely attenuated. In addition, the literature indicates that human subjects are more sensitive to lower frequency than higher frequency vibrations, with maximum sensitivity to lateral motion occurring in the 1.25-2.0Hz band. These characteristics combine to make the human body very sensitive to wander-induced vibrations.

3) Wander is measurable as a low-frequency, low-amplitude phenomenon. Typical wander behavior is observed in the frequency band 1-3Hz, which coincides with the band of frequencies amplified by the body and where the literature indicates that human subject are most sensitive too lateral vibration. Vibration magnitudes are dependent on many factors including sensor location, vehicle, tire type, and vehicle occupant characteristics and posture. For the testing conducted here with acceleration measured on the passenger's head, wander was generally associated with 1-3Hz waveforms with peaks greater than 0.75 m/s^2 (0.076g). These results are consistent with other literature reporting comfort thresholds for lateral vibration. Quantifying into two levels, no wander vs. wander, lateral RMS acceleration measured on the head of a 6'1" 175lb male subject increased 38% from 0.266 m/s^2 (0.027g) in non-wander areas to 0.365 m/s^2 (0.037g) in wander prone areas. Quantifying into three levels, no vs. low vs. high-severity wander, lateral RMS acceleration measured on the head of a 5'10" 175lb male subject increased 16% and 38% from 0.255m/s^2 in non-wander area to 0.297 m/s^2 and 0.349 m/s^2 in low and high-severity wander areas, respectively.

4) The most effective sensor location to capture vibrations due to vehicle wander proved to be the passenger's head. This location takes advantage of the human body's amplifying and filtering characteristics. This placement also takes advantage of the fact that since the negative feedback arises with vehicle occupants, measurements of vehicle occupant vibrations, as opposed to vehicle vibrations, which can be quite different, will correlate most closely with the vibrations that lead to the feedback. If body measurement is not desired for this reason, the seat frame is recommended. It is important to understand that vibration levels, when measured on the body, are vehicle occupant dependent.

5) The standard analysis procedures recommended in ISO-2631 did not prove to reliably capture vehicle vibration changes due to wander. Further, even though CDOT customers have indicated that wander is uncomfortable, the ISO analysis results in a rating of "not uncomfortable." This discrepancy is due to the undesirable seat cushion sensor location and environmental factors that are not taken into account by the ISO procedures.

6) Given that other sources of lateral vibration (e.g., wind, steering input) can lead to similar acceleration behavior to that of wander, and the fact that vibration amplitudes are dependent on many factors, it remains important to have human input when performing wander assessment. Human assessment of wander has proven to be a valuable component of the wander evaluation system. If measured acceleration data alone is used, false positives will likely exist.

5.1 Recommendations

It would seem very difficult to eliminate wander completely if longitudinal tining is present. There is great variation in tire tread patterns and even small variation in tining grooves can result in a very different response than that designed for by tire companies. If the goal is to determine whether or not wander exists for a certain stretch of roadway, given the difficulty in reliably and consistently quantifying wander, CDOT should consider relying solely on human assessment. Human judgment appears accurate and reliable, i.e., the existence or non-existence of wander is clear and obvious to a passenger. If it remains desirable to develop a standard method to measure and quantify wander, the following should be kept in mind:

- Wander is vehicle-specific, so any efforts to standardize wander measurement need to employ a consistent, specific vehicle
- The best location to place an accelerometer to capture vehicle wander is the passenger’s head
- Since vibrations are subject and posture dependent, subjects (or possibly an anthropomorphic test dummy) need to be similar in size and given specific instructions regarding posture

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