Effects of Roadway on Driver Stress: An On-Road Study using Physiological Measures

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2013

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Program Authorized to Offer Degree:

Civil Engineering

University of Washington

ABSTRACT

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There has been a great deal of research expended on enhancing our roadway to ensure that road users are provided a smoother, more enjoyable ride. One area that has not been well examined is the relationship to safety and stress. Human factors research shows that driver stress is associated with workload and fatigue, and is constructs that can have an impact on overall driver safety. The goal of this study was to examine whether there are different levels of driver stress across various roadway conditions. This goal is achieved using data collected from an on-road study with 60 drivers from three age groups (less than 25 years old, 35-55, and 65 and older). Physiological measurements associated with driver heart activity (ECG) were recorded and used as an indicator for cognitive workload. Patterns in stress responses were evaluated across age and gender for inverse trip sets along a pre-defined route. A heart rate variability (HRV) analysis was performed and both time and frequency domain parameters were examined. Short interval stress was used to assess trends in stress by distance traveled. Longer intervals were used to reflect induced stress from roadway characteristics. It was determined that the HRV parameters in conjunction with each other are stable indicators of mental workload. Similar responses were observed across all genders and ages, however the older age group had the largest incremental changes in physiological responses. Evidence suggests that drivers experienced increased cognitive demand along rough pavements (verified through IRI values) and through tunneled roadway segments. It was also conclusive that the route was short enough that fatigue induced by long duration driving was not significantly captured and thus the clockwise and counterclockwise data sets could be compiled into a singular HRV analysis.

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CHAPTER 1: INTRODUCTION

1.1 Overview

This research seeks to validate the need to examine roadway designs from a human factors perspective; specifically by evaluating how various roadway surface conditions impact driver behavior.

This study was designed in response to the current direction in research and capital projects for enhancing road smoothness and overall quality. However, little research has actually been done in evaluating the impact that road smoothness has on the driver. The study was arranged such that four road surface types were investigated:

- Relatively newly paved asphalt and Portland cement concrete (PCC) (Interstate 90)
- Older PCC under high volume conditions (I 5)
- Road laid over water that encompasses various rough segments due to construction through an environmentally-rich context (State Route 520)
- Fresh asphalt mix in rural area, through wetlands and a low density area (Bellevue, WA residential roads)

These pavement types were chosen under the hypothesis that an association exists between surface roughness and driver stress. Therefore this selection provided a good myriad of surface conditions to examine with respect to driver stress. It is further hypothesized that rougher roads is associated with increased stress, but also a road that is actually too smooth may not provide enough cognitive stimulation and thus lead to more startling individual stress events. In these hypotheses, rough roads are defined as roadways with high levels of vibrations and/or noises resulting from driving over them. Factors that influence pavement roughness includes exposure of course aggregate, joints, transverse cracks, longitudinal cracks in wheel way, and use of pavement grinding.

There are two themes identified by Matthews & Desmond (1995) that is particularly relevant to our understanding of driver stress: overload of attention and disruption of control. Pavement type can actually relate to both aspects. For example, roads that generate excessive vibration in your vehicle can overload driver attention and the overall workload of the driving task increases. Whereas, roads that are relatively smooth can generate disruption of control with even minor degradations in the road. Driver stress provides insights on driver behavior by quantifying cognitive workload and predicting risky coping strategies. Selzer & Vinokur (1975) concluded that driver stress is a significant safety problem for the system, and should thus be explored. Since then, numerous studies have confirmed that stress is associated with breakdowns in driver performance (Reimer & Mehler, 2011; Mehler, et al., 2010). Specifically, stress may impair performance by eliciting more risk taking behavior to cope with added stress. This could manifest itself into greater distractions from the primary driving task, and inducing potentially precarious coping strategies (e.g. reacting aggressively), and ultimately increase crash risk (Matthews, et al., 1999a; Norris, et al., 2000). For the purposes of this study the distinction between eustress and distress was made. Eustress, which is a good stress (e.g. joy), was disregarded and only distress was considered (Kopin, et al., 1988).

In human factors research, it is commonly acknowledged that age-related and gender-related factors impact our driving styles (Elander, et al., 1993; Boyce & Geller, 2002; Glendon, et al., 1996; Yan, et al., 2007) and likelihood of being involved in a crash or severe injury (Hill & Boyle, 2006; Ryan, et al., 1998; Lourens, et al., 1999, Chliaoutakis, et al., 2002; Matthews, et al., 1998). Therefore this study deemed it important to evaluate surface conditions and stress by gender and age. Specifically three age groups (younger, middle, and older) were constructed, each balanced by gender.

Stress has an impact on heart activity, by increasing heart rate and decreasing heart rate variability (Berntson, et al., 1997; Lee, et al., 2007b; Mulder, 1986). There are many physiological measures of the driver's heart activity and one way to collect this type of data is using electrocardiogram (ECG). Collecting this physiological signal was the superior technique for providing continuous feedback about the drivers without interfering with their task performance (Healey & Picard, 2005). This minimal to no disturbance in task performance was a key factor in selecting to monitor heart activity, especially in comparison to an electroencephalogram (EEG) measurement, recording electrical activity of the brain, which required participants to drive wearing a head cap. Furthermore, a heart rate variability analysis was particularly applicable for this study as it is a strong indicator of mental stress or workload caused by driving tasks (Apparies, et al., 1998; Mulder, 1992). Within the heart rate variability analysis, both time (statistics of the intervals) and frequency (power spectral analysis) domain parameters were evaluated. Both of these domain parameters were used as a means to provide validation for study results.

1.2 Significance

By uncovering critical links between pavement conditions and driver behaviors, we can pave our roads in a way that increases safety for all users and more efficiently utilizes capital funding. Safety is a crucial component in this because correlations have been identified between driver stress and an increased crash risk (Norris, et al., 2000). According to AASHTO (2009), "only half of the nation's major roads are in good condition and one in four urban roads is in poor condition." With this being the case, it is inevitable that a vast amount of capital spending will fund surface maintenance projects. Prioritization and efficiency is critical in executing these projects.

In order to fully understand the complexity of the relationship between surface characteristics and driver behaviors, this study closely examines various yet realistic pavement conditions, influences of driving behaviors, and dimensions of stress.

1.3 Study Scope

The scope of this research was to explicitly consider pavement conditions; therefore the design of this study consciously minimized the occurrence of external effects. Figure 1below illustrates the controlled variables deliberated in order to isolate the unwanted factors.

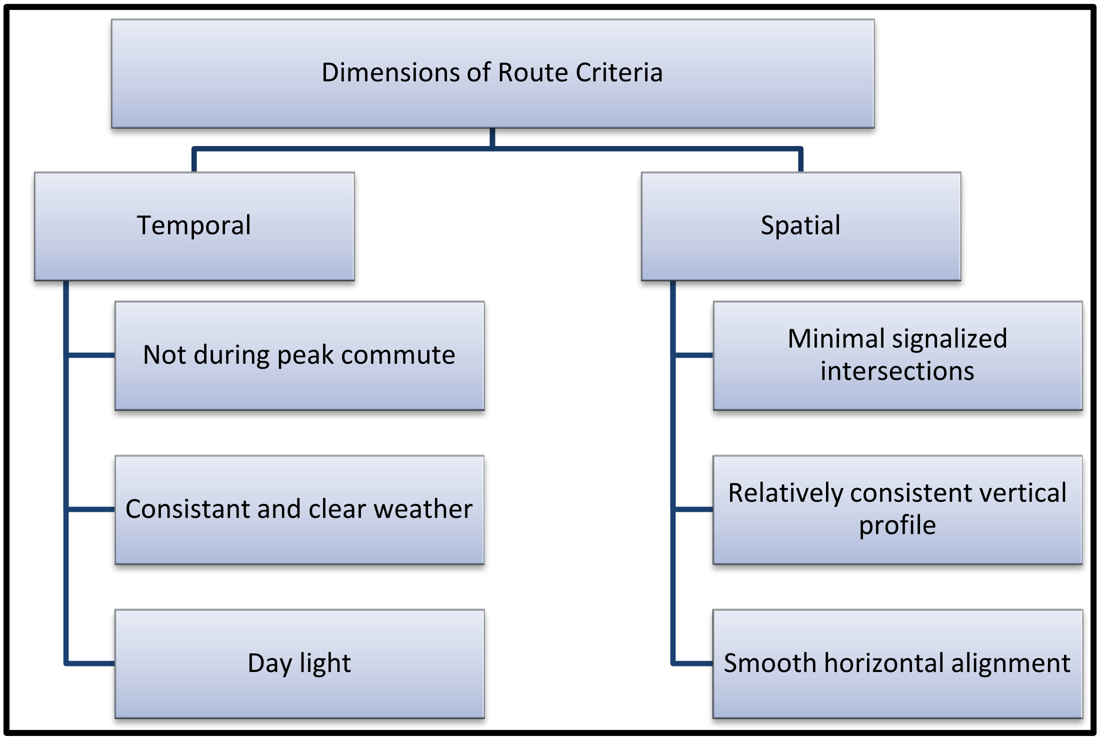

Figure 1: Exclusion tactics for variables outside study scope

1.4 Research Objectives

The primary focus of this study was to assess how drivers respond (objectively and subjectively) to roadway surface conditions to address the following research questions:

- At what point do drivers become noticeably and adversely affected by surface conditions?
- How do the physiological measurements compare to the drivers perception of the road?
- How does the correlation between stress and the road vary across age and gender?
- Can a road be too smooth, causing the driver to not adequately focus on the task at hand?

This thesis is divided into five chapters and begins with a literature review to justify the value of conducting this study. A description of the experimental protocol and data analyses methods used to assess driver stress on various pavement types is then presented, followed by the inferential outcomes. The thesis concludes with the overall insights gained and its relevance for potential future work.

CHAPTER 2: LITERATURE REVIEW

The justification for this thesis is based on studies that have examined pavement condition and noted differences in acceptable noise level, driver behavior and crash risks, and measurements of behavior based on subjective and objective measures, and well as the fiscal relevance. This chapter summarizes the relevant literature reviewed to create this basis.

2.1 Driver Stress

Lazarus and Folkman (1984) defined stress as “a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being.” Matthews (2001) expanded on the person-environment interaction component of the cognitive process and found stress reactions can be categorized into primary (personal significance of events) and secondary (coping ability) appraisals. Moray (1979) suggested that mental workload was an inferred construct that integrates task difficulty, operator skill, and observed performance. However, as Kantowitz & Simsek (2001) pointed out, workload is too difficult to directly observe and rather should be inferred from changes in performance. Therefore, physiological measures are recorded and analyzed in studies that evaluate driver stress.

2.1.1 Impacts on Driver Safety

Understanding driver behaviors provide insights on predicting and enhancing highway safety. Driver behavior is influenced by several factors, one component being driver distraction. Driver distraction is defined as something that “diverts the driver’s attention away from the activities critical for safe driving” (Regan, et al., 2009). It is therefore reasonable to conclude that unnecessary stress onto a driver is a form of driver distraction.

According to a report issued by NHTSA, 16% of fatal crashes and 21% of injury crashes in 2008 were attributed to driver distraction (Ascone, et al., 2009). Particularly, it has been noted that many of these crashes are correlated to impaired driver cognition due to fatigue, stress, or mental workload (Partin, et al., 2006). Therefore, by evaluating stress as a form of distraction, this study addresses the safety impacts of roadway surface conditions.

More specifically, distraction can be further categorized as visual (e.g. reading directions), auditory (e.g. conversing with a passenger), biomechanical (e.g. adjusting the radio), and cognitive (e.g. being lost in thought) (Ranney, et al., 2000). Several studies have evaluated driver stress as a cognitive distraction and have concluded that distress may lead to impaired decision-making capabilities (Baddeley, 1972), decreased situational awareness (Vidulich, et al., 1994), and degraded performance (Helmreich, et al., 1990). Through the use of physiological parameters (e.g. heart rate) the cognitive state of a driver can be accurately monitored (Partin, et al., 2006).

The following figure, Figure 2, illustrates the relationship between driving performance and workload. This concept compiled by the MIT AgeLab is an adapted model of the Yerkes-Dodson law (Coughlin, et al., 2011). By evaluating the stress overload imposed by pavement characteristics, this study addresses the far right end of the curve, which denotes a significant degrade in driver performance.

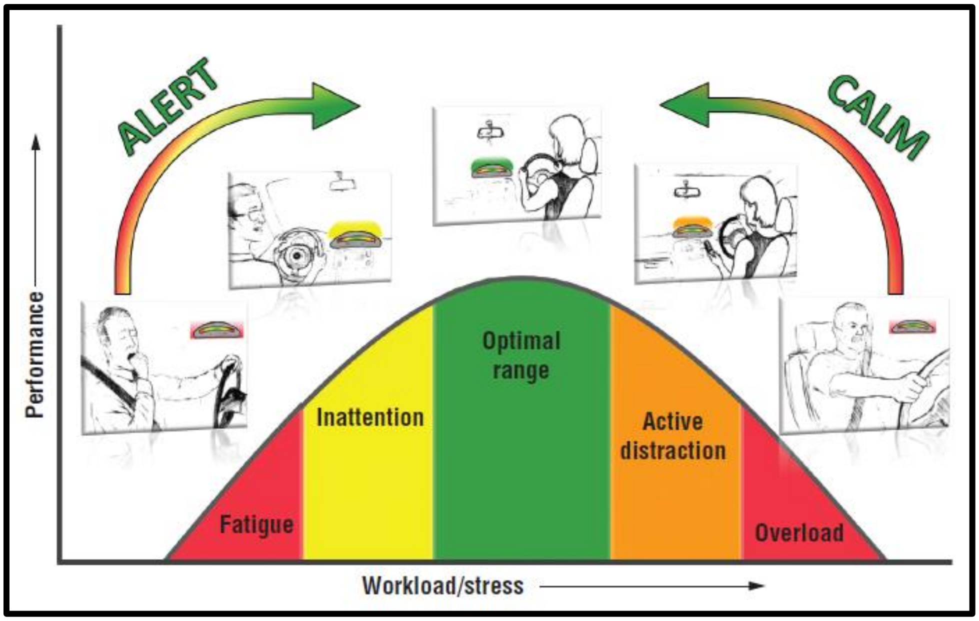

Figure 2: Effects of workload on driver performance (Coughlin, et al., 2011)

Matthews et al (1998) hypothesized about traits established in the Driving Behaviour Inventory (DBI) and their probable consequences, based on cognitive stress processes. This work found that stress associated with the dislike of driving was related to lateral positional variability and control errors, but reduced risk taking; aggression was strongly related to speed and frequency of high-risk overtaking tasks, but unrelated to performance on the open-road; high cognitive alertness resulted in quicker hazard detection.

2.1.2 Ways to Measure Stress

Measures of driver stress can be objectively captured using physiological measures. Physiological measures can be used to quantify changes in the body's state. These measures can include skin conductivity, cardiac, neurological, muscle, and respiratory activity. Mehler et al (2010) concluded that monitoring physiological based measures offer an objective and continuous analysis in a dynamically changing situation. Furthermore, measurements of the heart are the most practical for application in the driving domain as it least interferes with driving performance (Healey & Picard, 2005). Observation also concluded that heart data was less expensive, invasive, and more portable to collect; specifically compared to brain mapping (electroencephalogram or EEG) and muscle activity (electromyography or EMG).

Electrocardiogram (ECG)

Electrical activity generated by the heart is referred to as an electrocardiogram, or ECG, signal. This signal offers important information about the body's state (Lee, et al., 2007b). The mechanism used to record this signal is called an electrocardiograph, the Biopac MP150 in the case of this study.

Each component of the cardiac cycle contributes to the ECG output, creating the graphical representation that most everyone would recognize. The figure below provides an image of each step in the cardiac cycle and its consequent impact on the ECG waveform.

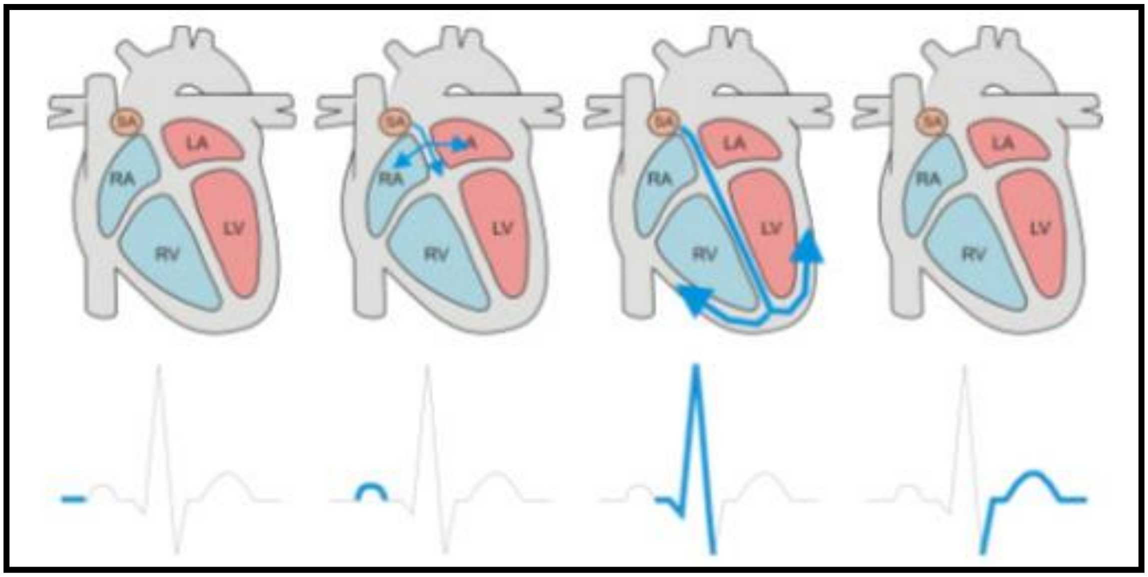

Figure 3:Cardiac cycle (Biocom, 2009)

Furthermore each element of this wave has an associated name: P, Q, R, S, and T. Each of these smaller waves, represented by the preceding letters, allow experts to discuss the heart rhythm using intervals (e.g. PR interval). This is best portrayed below in Figure 4, which illustrates the various components of the ECG wave.

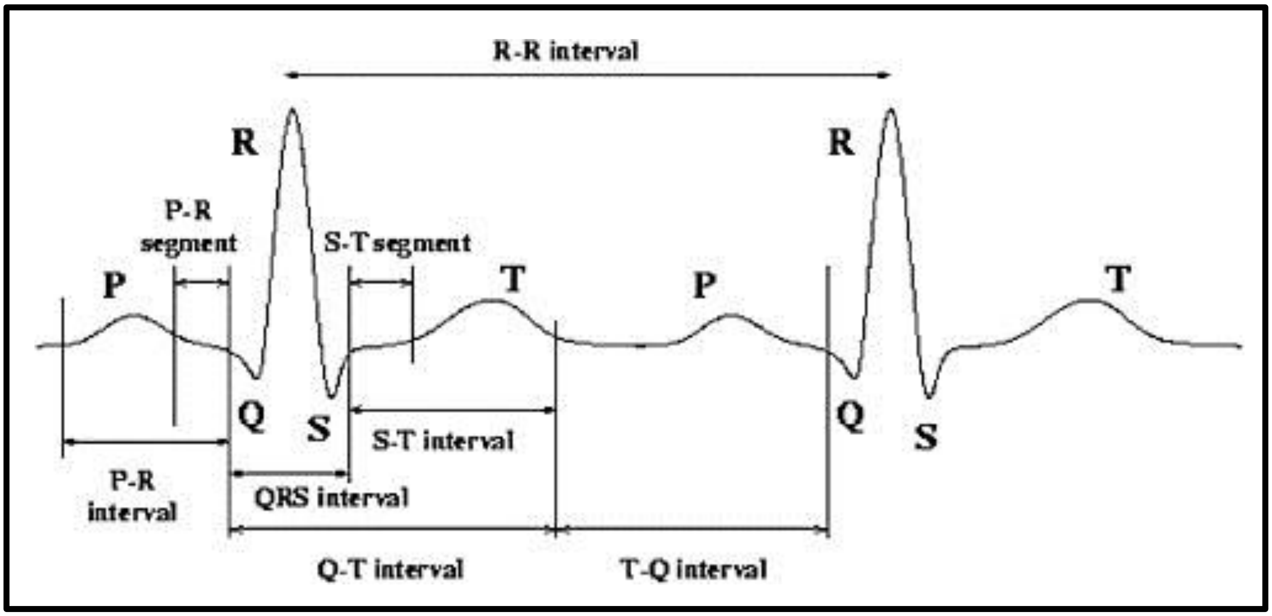

Figure 4: ECG waveforms dissected (Javadi, et al., 2012)

For the purposes of this study, we are interested in the R-wave peak. This peak is used in calculating heart rate (e.g. counting the number of R-wave peaks, expressed in beats per minute). The R-wave peak can be further analyzed to generate heart rate variability, which describes the "variation over time of the period between consecutive heartbeats" (Acharya, et al., 2006). This is often referred to as the RR interval or RRI.

Zhao et al (2012) found that human heart rates violently fluctuate during a mental stress situation. Mehler et al (2010) indicated that the physiological measures can quantify changes in workload prior to exhibits of overt performance breakdowns. This deems physiological monitoring a useful tool in that it does not require the participant to engage in a safety critical event in order to display signs of cognitive distraction and overload. More specifically, an analysis of heart rate variability was selected because "previous studies have reported that heart rate was the most sensitive cardiovascular index of workload and fatigue associated with driving a vehicle" (Apparies, et al., 1998).

Autonomic Nervous System

Variations in heart rate is triggered by responses from the body's autonomic nervous system, or more specifically it is a reflection of the interplay between the sympathetic (low-frequency) and parasympathetic (high-frequency) nervous systems (Kleiger, et al., 2005; Bilchick & Berger, 2006).

The autonomic nervous system is responsible for controlling and regulating the internal organs (e.g. the heart) without conscious recognition from the individual (Kleiger, et al., 1992; Tattersall & Hockey, 1995). It is composed of two antagonistic sets of nerves, the sympathetic and parasympathetic nervous systems (Steptoe & Sawada, 1989). The first is associated with an increase in heart rate (Ohsuga, et al., 2001), while the latter acts to slow the heart rate (Pagani, et al., 1995).

Typically, the sympathetic nervous system is triggered during a tense state, while the parasympathetic nervous system works in states of mental peace (Zhao et al, 2012). For example, a driver in a state of cognitive distraction such as thinking or talking would have a decreased heart rate RRI induced by the acceleration of their sympathetic nerve (Miyaji, et al., 2010).

Heart Rate Variability

"Heart rate variability (HRV) describes the variations between consecutive heartbeats" (Niskanen, et al., 2004). Numerous researchers have used this physiological measurement to assess driver workload under diverse driving conditions (Zhao, et al., 2012; Li, et al., 1995; Li, et al., 2004). Hartley et al (1994) examined physiological and psychological changes in truck drivers based on HRV. Healey & Picard (2005) used HRV to recognize three general levels of stress (i.e. low, medium, high) using minute intervals of data during segments of rest, city, and highway driving. Changes in heart rate have been noted during certain driving tasks (Hartley, et al., 1994; Liu, et al., 2004). Similarly, Apparies et al (1998) showed that heart rate and HRV may serve as early indicators of fatigue. In general, HRV specifically measures mental workload, while HR more broadly measures physical workload (Wickens, et al., 1998).

Many studies have concluded that during periods of increased stress, there tends to also be an increase in the values of heart rate and the low to high frequency ratio (Jorna, 1993; Lee, et al., 2007b; Healey & Picard, 2005; Sloan, et al., 1994). It has been suggested that this is because the sympathetic nervous system, which again is related to the low frequency (LF) power, is activated during stress (Lee, et al., 2007a). However, other heart rate variability parameters (such as SDNN, RMSSD, pNN50) decrease in value for increasing stress (Lee, et al., 2007a; Lee, et al., 2007b).

Furthermore, some studies have suggested that heart rate increases and heart rate variability decreases with distance driven (Simonson, et al., 1968; Egelund, 1982). In a five day study, O'Hanlon (1972) found that heart rate variability increased with drive time, descended after alerting events, was minimally influenced by traffic event frequency, and inconclusively may have been effected by geometric configuration. Many of these studies attribute driver alertness/fatigue to be at the origin of these trends.

There are two common approaches for analyzing heart rate variability, using frequency domain and time domain parameters. These are further expanded upon in the following subsections.

Frequency Domain

Frequency domain analysis calculates the power spectral density of the RR series, based on powers and peak frequencies for different frequency bands. There are three frequency bands most commonly used, very low frequency (VLF), low frequency (LF), and high frequency (HF) (Niskanen, et al., 2004). For this study, only low frequency and high frequency bands were considered. These two frequency bands are described below in Table 1.

Table 1: Frequency power bands summarized from Acharya et al (2006)

Frequency Band	***Power Spectrum (Hz)***	***Reflects***
Low (LF)	0.04 – 0.15	Sympathetic tone: • Response to stress, exercise, and heart disease • Causes an increase in HR
High (HF)	0.15 – 0.40	Parasympathetic (vagal) tone • Resulting from the function of internal organs, trauma; caused by spontaneous respiration • Decreases HR • Provides a regulatory balance in autonomic function

The power distributions across the frequencies can be reported using several different parameters. The most common ways to report frequency domain analysis is provided in Table 2 below.

Table 2: Frequency domain parameters summarized from Niskanen et al (2004)

Variable	***Units***	***Description***
Peak Frequency	Hz	Power spectral density estimate for VLF, LF, and HF frequency bands
Power	ms^2, % and normalized units	VLF, LF, and HF frequency bands in ms^2 and percentage value. LF and HF can also be represented in normalized units (n.u.)
LF/HF		Ratio of LF and HF frequency band powers in ms^2

A number of driving studies that reported results including a frequency domain analysis used the low to high frequency (LF/HF) ratio parameter. This variable provides a means to measure the interplay between the sympathetic and parasympathetic balance (Kleiger, et al., 2005). In other words, it shows the interaction between sympathetic activity and parasympathetic activity. An increase in the sympathetic tone, which would represent a response to a stress event, would also increase this ratio. Similarly, a lower valued ratio would imply a less presence of stress events.

It is important to acknowledge that some research has indicated a gradual decrease in total power of heart rate variability as adult's age. However further exploration of this verifies that the ratio of power in the bands remains unchanged (Cerutti, et al., 1995; Akselrod, 1995). Therefore, since this ratio remains stable with age, a low frequency to high frequency ratio comparison between subjects is still applicable for this study.

Time Domain

The other application of heart rate variability is using a time domain analysis. The parameters within this analysis are "calculated directly from the raw RR interval time series"

(Niskanen, et al, 2004). In contrast to frequency domain parameters, these variables are functions of time.

Most driving studies focus on these time-domain parameters. This is because frequency-domain parameters require longer interval recordings, which is not necessarily a practical application in real traffic and road conditions. In most transportation situations, drivers get acute stress in a moment and then recover; this yields time-domain parameters to be a more accurate reflection of the driver's state (Tarkiainen, et al., 2005).

There are multiple ways to evaluate the heart signal in regards to time, which can include comparing mean values for between R-peaks, similarly for variations in RR intervals, and specifically evaluating adjacent RR intervals. Descriptions of the variables used specifically for this study are provided in Table 2.

Table 3: Time domain parameters summarized from Niskanen et al (2004)

Variable	***Units***	***Description***
SDNN	ms	Standard deviation of the selected RR interval series
RMSSD	ms	Root mean square of differences of successive RR intervals
pNN50	%	Percentage value of consecutive RR intervals that differ more than 50 ms

In this study, these above values were calculated from each participant's raw ECG data for intervals corresponding to roadway segments of interest (e.g. I-5, I-90, etc.).

2.1.3 Variables that Influence Driver Stress

Driver stress is impacted by several factors, for this study we will categorize this into four influences: vehicle, drivers, traffic and the roadway.

Vehicle

Advancements in technology have led to an increased deployment of in-vehicle systems aimed at improving safety, such as navigation, guidance, and collision-avoidance systems. These systems aim at minimizing stress by reducing the frustration from congestion, assist drivers in finding the most efficient route, and provide drivers with warnings to avoid safety-critical events (Matthews & Desmond, 2001).

However, these systems also result in excessive information presented to the driver or may cause an over trust of the system which may lead to misuse (Kantowitz & Simsek, 2001; Parasuraman and Riley, 1997). Several studies investigate these trade-offs between the benefits of in-vehicle systems and their potentially hazardous consequences. Kantowitz and Simsek (2001) emphasized the importance of evaluating driver workload in the presence of this new technology. Matthews and Desmond (2001) explored a new type of stress introduced by these systems; stress induced as a result of "difficulty relinquishing and taking over control of the vehicle."

Driver

There are many studies that show that age-related factors and differences in gender greatly impact crash risk and the likelihood of severe injuries. For example, younger drivers are attributed to partaking in riskier driving behaviors, while older drivers are attributed to making errors related to decreased situational awareness. In a questionnaire study, Yagil (1998) found that younger drivers expressed significantly lower levels of motivation in complying with traffic laws as compared to older drivers. In a study regarding advanced traveler information systems, results indicated drivers over 65 years old drove slower and more cautiously while concurrently driving and navigating. However, despite this increase in caution, these older drivers made more safety related errors as compared to the younger drivers (Dingus, et al., 1997). Bao and Boyle (2008) showed that older and younger drivers were more likely to run stop signs and less likely to yield at medians as compared to middle-aged drivers. Furthermore, studies have identified relationships between the severity of crashes and age. It is suggested that crash severity, specifically fatality crashes, increase with increasing age, specifically older people as compared to younger (Ryan, et al., 1998; Evans, 1991).

With regards to stress, several studies have evaluated how vulnerability to stress varies across age groups (Matthews, et al., 1999b; Simon & Corbett, 1996; Westerman & Haigney, 2000; Kontogiannis, 2006). In a survey study, Westerman & Haigney (2000) reported that younger drivers were highly likely to convey stress in the form of aggression, while older drivers expressed stress through dislike of driving and situation-specific tension. Hill and Boyle (2007) showed that older drivers typically report higher levels of stress, with the exception for the condition of interactions with other drivers. This implies that older drivers are less likely to experience road rage, which is consistent with other literature. Therefore in an effort to equally capture the most vulnerable to stress and crash risk age groups, younger and older ages were included in the scope of this study. Furthermore, the middle age group was also included to provide a control and keep balance for reflecting findings across the entire driving population.

Studies have also shown that young male drivers typically respond differently under stress when compared to females (Hennessy & Wiesenthal, 1997; Ivancevich, et al., 1982). For example, under driving conditions women generally report greater stress-related tension, but are less likely to exhibit aggressive or violent driving behaviors (Matthews, et al., 1999b; Smart, et al., 2004). Hill and Boyle (2007) found gender to be a significant predictor of stress levels, specifically under adverse weather conditions, poor visibility, and performing driving tasks.

Traffic

Traffic has an effect on headways, trip time, sight distance, and requires increased awareness to respond to other vehicle maneuvers. A number of studies have evaluated the effects of traffic on driver stress. Heavy traffic (e.g. rush hour congestion) is interpreted by many drivers as stressful (Hennessy, & Wiesenthal, 1997). This is a relevant concern, based on 2009 United States Census Bureau data, McKenzie & Rapino (2011) reported that 86% of the workforce transported to work in a car, truck, or van, of which 76% were single occupant. Furthermore, Gulian et al (1989) found that among U.K. highway drivers, 50% experienced irritation in traffic jams independent of being in a hurry. A number of studies also found correlations between stress and delays associated with congestion (Stokols, et al., 1978; Turner, et al. 1975). Matthews & Desmond (2001) hypothesized that the difficulty to maintain a safe headway in fast moving, high-density traffic influenced stress. In a survey study evaluating why older drivers give up driving, Hakamies-Blomqvist & Wahlström (1998) found that older drivers reported high levels of stress associated with driving in rush hour – especially in older female drivers. In an interview study assessing high and low congestion conditions, state driver stress and aggression were greater under high congestion conditions, in comparison to commutes in low-congestion (Hennessy & Wiesenthal, 1999).

Roadway

In civil engineering, road geometry is often correlated to accident rates; for example, increases in crashes are seen along sharp curves with little to no shoulder as compared to a slight curve with adequate shoulder space. However, not as much human factors research has gone into exploring the effects of road geometry, specifically on driver workload.

Kantowitz and Simsek (2001) suggested that odd road geometry contributes to driver workload. Several researchers have defined the specifics of “odd road geometry.” Neuman (1992) proposed that radius of curvature, lane width, and shoulder width effected driver stress. Messer, et al (1979) found a relationship with sight distance. Hulse et al (1989) proposed that road width and distance of closest obstruction to road also influenced this. Matthews & Desmond (2001) specifically stated that road alignments, such as badly cambered [horizontal and vertical] curves and intersections with poor visibility, often cause drivers to worry and thus inducing stress.

2.2 Subjective Measures of Stress

There are two types of subjective reports for driving performance: observer reports (generally given by experts) and self-reports by the drivers (Brookhuis and De Waard, 2001). Self-reporting [through surveys and interviews] is a widely used means for collecting data in transportation studies. This type of data is relatively easy to obtain and requires no esoteric knowledge. However, a major disadvantage to survey data is that people are often unaware of internal changes (Brookhuis and De Waard, 2001). This is an exceptional weakness when applying self-reporting to reflect stress. In a driving test monitored after administering antihistamine, Brookhuis et al 1993 found that subjects performed significantly worse than those under placebo; however self-reporting showed they were not aware of their reduced alertness and although they were only slightly aware of impaired performance, they did not indicate more effort to compensate. This is certainly not to say that self-reporting is insignificant; it is just important to understand potential weaknesses in order to properly apply self-reporting.

In fact, several researchers have successively used self-reporting data to understand driving behavior and safety. Hill and Boyle (2007) used data from a national survey to understand different driving tasks and roadway conditions that may influence the driver’s perceived stress. This national survey was originally administered with the intent to define user information requirements for an advanced traveler information system (Ng, et al., 1995). Matthews et al (1989) developed a questionnaire called the Driving Behaviour Inventory (DBI) to study dimensions of driver stress. From the DBI, the main factors identified for stress were aggression, dislike of driving, and alertness.

2.3 Driver Performance Measures

There are many different driving performance measures that can be used to understand driver differences on-road. In an extensive series of studies, Bao and Boyle (2008) used braking patterns as a performance measure with respect to three age groups (younger middle and older). The specific measures used were brake pedal differential time (s), maximum deceleration (m/s^2), initial brake point (m), and complete stop (yes or no). Similarly, Bao and Boyle (2009b) used initial braking point (in meters), mean speed (m/s), complete stop (yes or no), number of head movements toward the left and right (in counts), and checking review mirror (yes or no) in older drivers to examine their behavior at intersections of rural expressways. Lastly, Bao and Boyle (2009a) examined age-related differences in visual scanning (proportioned into seven possible viewing regions) during three separate maneuvers (going straight across, making a left and making a right turn) at two median-divided highway intersections.

Noy (1989) evaluated drivers in a simulator based on workload measures reflected in standard deviation of lateral position, lane exceedance ratio, time to line crossing, headway, velocity, standard deviation of velocity, perception task reaction time, and memory task reaction time. Brookhuis and De Waard (2001) also stated that the amount of variability in lateral position can reflect driver mental workload. Furthermore, Allen and Stein (1987) found that the standard deviation of the lateral position (SDLP) is closely related to the likelihood of getting in a crash due to lane departure. Boyle and Mannering (2004) used variations in speed to quantify effects of in-vehicle and out-of-vehicle traffic advisory information. Other applications of vehicle measures for reflecting driver stress include speed, steering reversal rate, visual detection of targets, and standard deviation of speed (Verwey & Veltman, 1996; Verwey, 1991).

Brookhuis et al (1994) found that reaction time was also a good indicator of driver performance. Brookhuis and De Waard (2001) pointed out that headway (in distance or time) to vehicles in front must be regulated by the driver; thus responding to the maneuvers of other vehicles requires perception and attention.

2.4 Pavement

Two key constituents in evaluating pavement as a variable include considering pavement conditions and designs. This section details literature regarding quality and appearance (condition) and types and applications (design).

2.4.1 Pavement Conditions

There are limited studies on the relationship between pavement conditions and driver behaviors. Most studies that do exist fail to investigate the effects of surface conditions on the driver’s cognitive state. However a significant amount of research investigates the acoustical components, such as advantages of asphalt over concrete (Kuemmel, et al., 1996), surface performance of ‘quiet’ pavements on improvements for highway neighboring residents (Lu, et al., 2010), and acceptability of surface noise by the public (Shafizadeh & Mannering, 2003). Similarly, several researchers have explored how sound stimulus may act as a countermeasure against driver fatigue (Zhao, et al., 2010). Environmental sounds, such as road surface noises, were included in the scope of these mentioned studies; however were not the principal focus. Landstrom et al (1998) reported that sound stimulus can reduce fatigue.

However, this lack of comprehensive research goes in contrast with the current trend of DOT expenditures funding paving projects. As a result, these pavement projects may not be optimal in improving roadway safety in respect to drivers. It is important to fully optimize these projects, as budgets are generally constrained. Therefore a system needs to exist in understanding the importance and prioritization of roadway projects (Eriksson, et al., 2008).

In the 1980s, the International Roughness Index (IRI) scale was established as an international measurement tool to report on pavement roughness (Sayers, et al., 1986). The scale begins at 0 meters/kilometer or inches/mile, with higher values indicating rougher pavements. Currently, jurisdictions use this standard to classify surface conditions and subsequently prioritize pavement projects (Shafizadeh & Mannering, 2003). However, a re-validation for this system in respect to driving behaviors is in order. This study provides the opportunity to compare how the reported IRI and recorded driver responses reflect each other.

It is important to note that as part of the experimental design, it was decided best if half of the participants completed the route clockwise and the other half counterclockwise. By observation, the individual segments within the route were symmetrical for inverse trip sets; that is, participants experienced the same conditions for both clockwise and counterclockwise directions of travel. Studies have explored the validity of compiling between subject data for differing route directions (e.g. clockwise vs. counterclockwise, northbound vs. southbound, etc.). Shankar & Mannering (1998) compared westbound and eastbound movements and found endogenous relationships within lane speeds and between lane speeds and speed deviations; yet dissimilar effects related to grade and temporal factors. This was a key element in justifying the split of route directions.

2.4.2 Pavement Design

Pavement design is a complex field, in which location, climate, lifespan, budget, and load factors all play a significant role; the design for a specific facility is a function of these factors.

In general, pavement surfaces can be classified into two categories: flexible (asphalt) and rigid (Portland cement concrete, PCC). The differentiation in flexible and rigid pertains to how the pavement distributes the load over the subgrade; a rigid pavement tends to distribute the load over a wider area as compared to flexible (Pavement Interactive, "Pavement Types"). Asphalt is a hydrocarbon produced from petroleum distillation residue, either occurring naturally or synthetically using crude oil. Asphalt binders, which include asphalt cement and additives, are used to lay asphalt pavement (Pavement Interactive, "Asphalt"). Common applications of asphalt include the following hot mix asphalt (HMA) designs: dense-graded HMA, stone mixture asphalt, and open-graded HMA (Pavement Interactive, "HMA Pavement").

Portland cement concrete on the other hand is much more rigid and deflects significantly less under loading. As a result of this it is more prone to cracking. There are three major designs for Portland cement concrete crack control: joint plain concrete pavement (JPCP), joint reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). The joint plain concrete pavement is the most commonly used of the three (Pavement Interactive, “PCC Pavement”). A significant component in Portland cement concrete design is in the use of admixtures, which alter the concretes natural properties, such as workability, setting time, strength, and durability (Pavement Interactive, “PCC Admixtures”).

Each of these pavement types and mix designs offer benefits and trade-offs. For example, flexible pavements often require maintenance every 10 to 15 years, whereas rigid pavements can serve 20 to 40 years with minimal rehabilitation (Pavement Interactive, “Pavement Types”). As a result of these lifespan attributes, Portland cement concrete is generally used in urban or high traffic areas. This is because maintenance repair projects are best minimized on high volume roads to avoid imposing additional delay. It is also important to note that asphalt maintenance is significantly cheaper and thus commonly used within smaller jurisdictions (e.g. local level as compared to federal interstate roadway). Furthermore, in applications of hot mix asphalt, dense-graded is usually used. However, stone matrix asphalt is useful in supporting heavy traffic loads and resisting studded tire wear (Pavement Interactive, “HMA Pavement”). In terms of this study, Portland cement concrete was observed across I-5 and most of I-90, while asphalt comprised a majority of the rural roads.

In recent years there has been a significant amount of work using open-graded HMA to create quieter pavements. Quieter pavements reduce the noise resulting from the tire/pavement interaction. Generally this is achieved by creating a negative texture, with the most common design being the open graded friction courses (OGFC). This design introduces air voids and rubberized asphalts to absorb sound (Pavement Interactive, “Pavement Noise”). Specific to this study, SR-520 was a test segment for quieter pavements just prior to construction within the corridor.

In general, asphalt is associated with a smoother ride because of its flexible nature. However, Portland cement concrete can be made smoother through the use of diamond grinding, longitudinal control cracking, making slabs the width of the lane, and strategically reducing friction. It is important to note that reducing friction too much imposes a new safety concern, especially for heavy vehicles.

2.5 Financial Relevance

Not only is safety a concern, but there also exists a fiscal imposition upon drivers under less than ideal pavement conditions. Several studies have investigated the financial benefits of smooth roads and verified this notion through improved fuel efficiency and reduced vehicle wear and tear. Additionally, it was found that “rough roads add an average of $335 to the annual cost of owning a car – in some cities an additional $740 more” (AASHTO, 2009). This, combined with user preferences of ride quality along a smooth road, leads to jurisdictions spending millions of dollars annually on roadway maintenance and repairs. AASHTO (2009) reported a savings of $6-$14 for every $1 spent in keeping a good road good as opposed to waiting to rebuild a deteriorated road. With over 3.9 million miles of public roads in the United States, even the most conservative estimate for the cost of a roadway maintenance project indicates a vast amount of money spent in this area (AASHTO, 2009). It is thus important to carry out a study that verifies the need to maintain a certain level of surface condition.

2.6 Summary

Creating these links between roadway surface conditions and driver behaviors will allow future projects to be more efficient and enable advancements in system wide safety. As previously stated, it is also important to understand how stress vulnerability varies across age and gender. The most pragmatic application of this is to monitor stress, using ECG recordings, across a wide variety of surface conditions; this is the notion that this study was built upon.

CHAPTER 3: METHOD

An on-road study using an instrumented vehicle was used for the data collection of this study. This chapter describes the participant, equipment, and experimental procedure used to assess driver stress over various pavement types.

3.1 Participants

Based on a power analysis from a previous and related study, a target sample size of 60 was considered reasonable for yielding statistically significant results. Therefore, this study recruited 60 drivers with Washington State licenses. Given constraints imposed by weather, construction, and traffic conditions, only 54 participants completed the drive. Volunteers were recruited within three age groups: younger (≤ 25), middle aged (35 – 55), and older (≥ 65). The sample had approximately an equal number of males and females within each age group. The route was completed in a clockwise direction by 24 participants, while 30 drove the loop counterclockwise.

Each participant was compensated $25 per hour for their involvement in the study. The experiment was approved by the University of Washington's Institutional Review Board.

The table below further exhibits the breakdown of each driving group by demographics of gender, age, and driving experience. This table provides information on subset sample sizes and their corresponding mean and standard deviation.

Table 4: Descriptive statistics

Age Group	**Gender**	**Mean Age** *(yrs)*	**Mean Driving Experience** *(yrs)*
Younger *(n = 20)*		22.0 (SD = 1.8)	5.6 (SD = 1.8)
	Male	22.3 (1.6)	5.5 (1.7)
	Female	21.6 (2.0)	5.6 (2.0)
Middle *(n = 20)*		46.2 (5.5)	28.5 (5.8)
	Male	45.3 (6.3)	27.6 (6.7)
	Female	47.1 (4.8)	29.4 (5.1)
Older *(n = 14)*		72.9 (4.3)	56.0 (4.2)
	Male	72.5 (4.6)	56.4 (4.5)
	Female	73.8 (4.1)	55.0 (3.8)

3.2 Equipment

The equipment required to complete this study included a vehicle, electrocardiograph, and computer software; this section further elaborates on each of these.

3.2.1 Instrumented Vehicle

The drive test was conducted in the University of Washington Human Factors and Statistical Modeling Lab's instrumented vehicle, which is a 2002 Ford Taurus with an automatic transmission. By using an instrumented vehicle as opposed to a driving simulator, the effects from pavement could be most accurately captured. A schematic of the vehicle instrumentation is provided below in Figure 5.

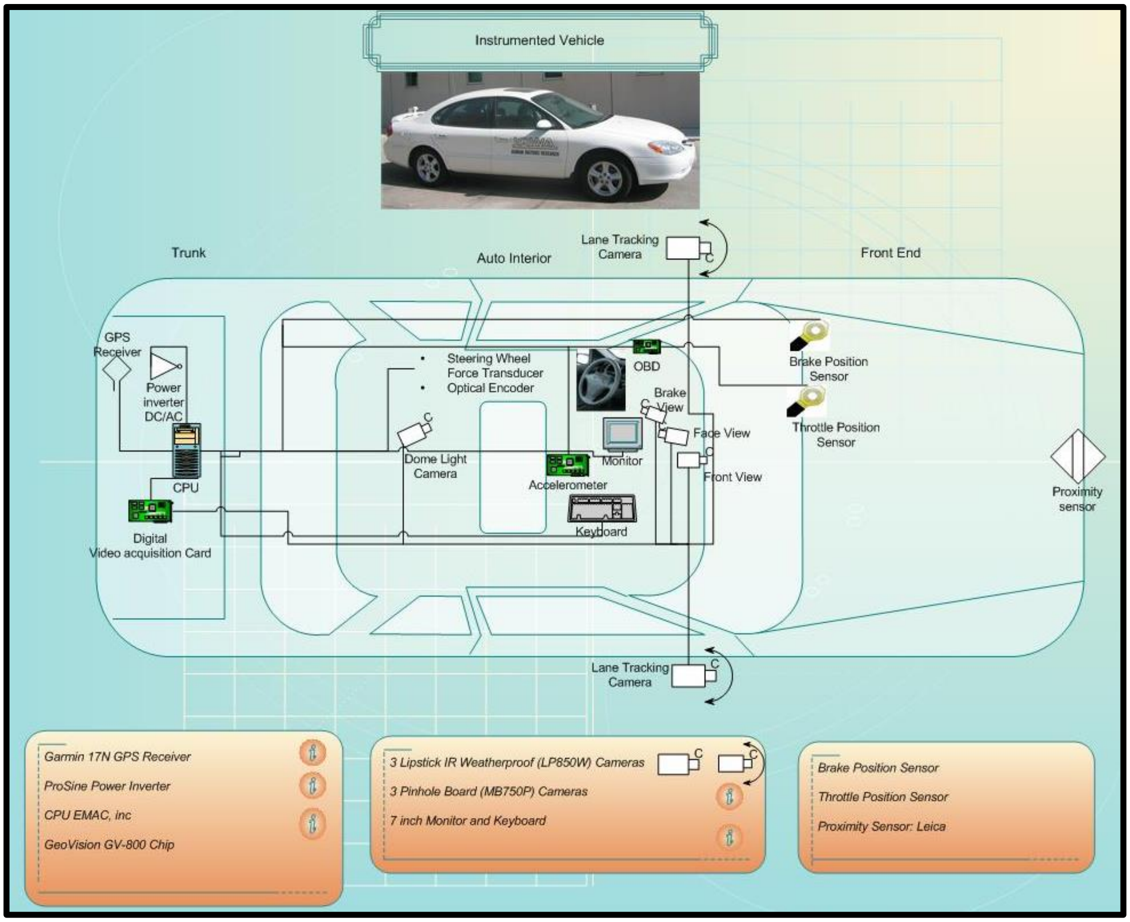

Figure 5: Schematic of the instrumentation (available at: http://depts.washington.edu/hfsm)

As shown from the figure above, this vehicle is equipped with an extensive array of data collection equipment. Measurements such as vehicle speed, engine RPM, throttle position, brake pressure, steering wheel position, GPS latitude and longitude, dimensions of acceleration, and distance traveled can be recorded by the equipped instrumentation. Additionally, the system records video data from seven cameras:

- Two pinhole cameras one mounted inside the rearview mirror and the other inside the driver's side b-pillar
- One camera under the steering column, focused on the driver's feet
- One mounted from the center ceiling of the backseat, directed forward at the driver

- One behind the rearview mirror, recording the vehicle's forward view
- Two recording lane position, each located on the side mirrors

All of the sensor and camera data was time stamped based on the internal clock of the data acquisition computer. The driver acquisition program, Lab View, was set to sample at a rate of 5 samples per second (5 Hz).

3.2.2 Biopac MP150

Driver ECG readings were recorded using a Biopac MP150 device (see Figure 6). This provided the physiological variables for the study, such as heart rate and heart rate variability. The MP150 served as the data acquisition unit. Attached to it was the Universal Interface Module UIM100C, which is used to connect amplifier modules to the acquisition unit. The amplifier used in this series was the ECG 100 C Amplifier, which is designed to pass the ECG signal with minimal distortion.

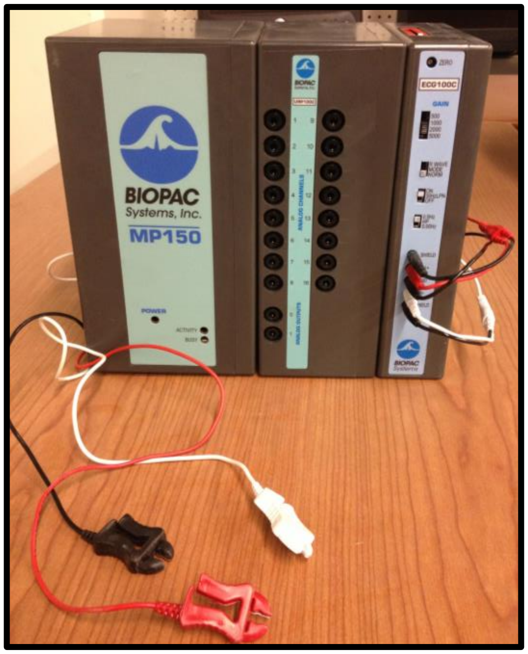

Figure 6: Biopac MP150

Specific settings on the ECG 100 C Amplifier were set in accordance to manufacturer's recommendations for use in heart rate variability applications. The gain was set to 1000, which controls the sensitivity of how amplified the signal is. The HP High Pass Filter was set to on, which is used to stabilize the ECG baseline. This is done by creating a low frequency threshold for which all signals must be higher in frequency to pass through (Bharadwaj & Kamath, 2011). The LPN Low Pass Filter was also set to on, which reduces noise from interfering signals – specifically the 50 to 60 Hz power line noise (Bharadwaj & Kamath, 2011).

The ECG data was time stamped based on the internal clock from the same computer that was used for collecting data from the instrumented vehicle. This data was collected at a sampling rate of 1000 Hz, which was the recommended rate from the manufacturer for heart rate variability analysis.

The software program AcqKnowledge was used for collecting and analyzing the ECG data. The acquisition computer was equipped with version 3 and the analysis computer with version 4.2.

The device was connected to participants via a Lead II configuration, which places three electrodes directly on the torso, which is a popular configuration for reducing artifact. Shielded leads, which are electrode cables designed to reduce noise, were used for the positive (placed over the lower left rib) and negative (just under the right clavicle) channels and an unshielded lead for the ground (just under the left clavicle) connection (Mehler, et al., 2010). The figure below illustrates this set-up.

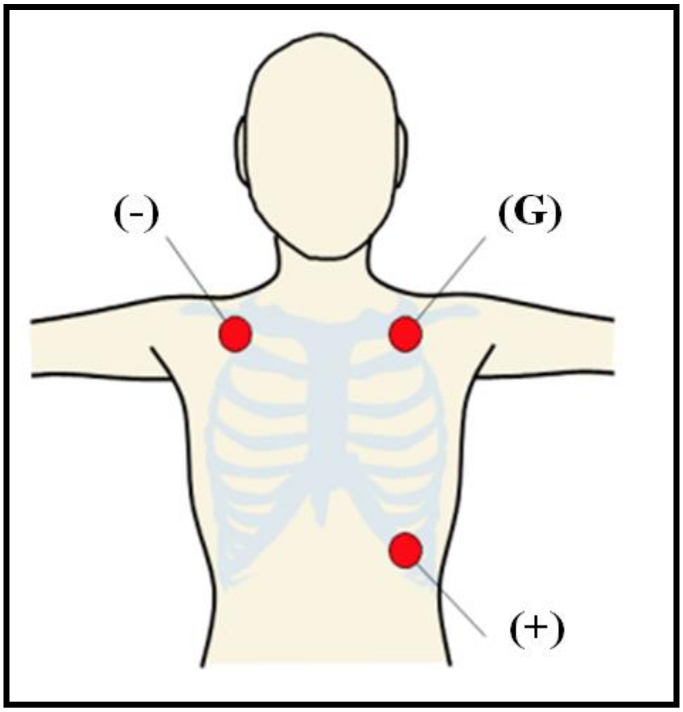

Figure 7:Lead II configuration (Miyaji, et al., 2010)

3.3 Route

The study drive was defined as a 25-mile circular route within the Seattle area, which took approximately 40 minutes to complete (see Figure 8). The route encompassed SR-520, I-5, I-90, I-405, and rural roads within Bellevue. Half of the participants completed the loop in a clockwise manner (SR-520 first), while the other half drove it counterclockwise (I-5 first). By using this same predefined route for all participants, the pavement conditions were controlled across participants. The use of clockwise and counterclockwise directions provides some randomization of the routes such that any differences in performance based on learning effects is minimized. The alternating routes also minimize the effects of current conditions from extraneous variables from uncontrolled traffic conditions and scheduled bridge drawspan openings. This is also consistent with the route directions used by Shafizadeh & Mannering, (2003).

Although this route did not include extreme variations in pavement conditions, the route was designed such that it represented realistic and common roadway pavement designs experienced in a daily commute. This setup allowed for the recorded physiological responses to be within the range of normal daily stress (Healey & Picard, 2005). Also, since the route was comprised of common infrastructure, the results from the study could be more broadly applied to other locations.

A map of this study route has been provided in the figure below.

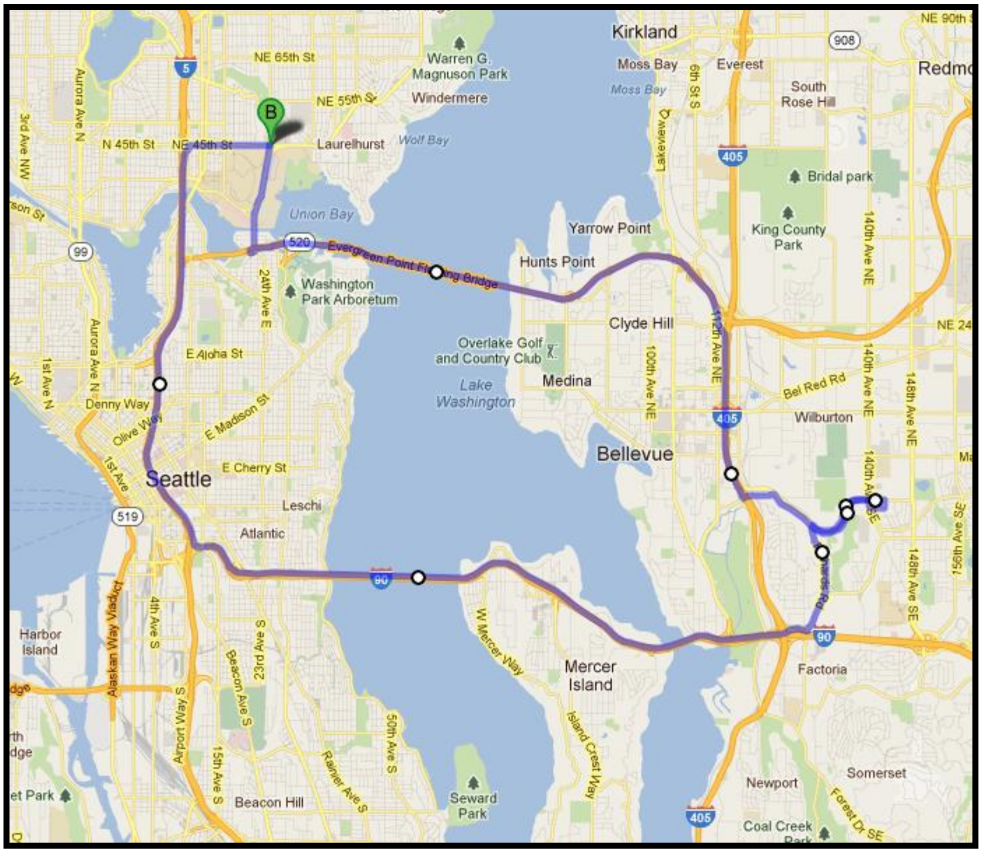

Figure 8: Driving route (Google Maps)

3.4 Segment Characteristics

The four areas of interest were selected for the diverse characteristics they offered within a reasonable distance. According to WSDOT (2011a), I-5 is the busiest freeway in the state with an average annual daily traffic (AADT) through the Seattle segment alone of over 200,000. This interstate is the main north/south highway for the state and is paved with Portland cement concrete (PCC) through this study's segment of interest. It has a posted speed limit of 60 miles per hour (mph). I-5 and I-90 both offer a divided reversible center facility for HOV traffic. I-90 is the main east/west interstate for the state with an AADT of at least 100,000 through the included segment (WSDOT, 2011a). This section is paved with both PCC and asphalt concrete, and encompasses a significant proportion of tunnels and bridges. Although it has a variable speed limit, the posted speed was 60 mph during each participant drive. SR-520 is one of two bridges (the other being I-90) that cross Lake Washington to connect the Eastside and Seattle. Half of the segment includes a floating bridge (posted speed 50 mph) with a newly implemented tolling system. The posted speed for the land portion of SR-520 is variable, but with a constant 60 mph for all participants. Prior to the toll implementation, SR-520 had an AADT of nearly 90,000 across the bridge (WSDOT, 2011a). It is also undergoing major construction, including a widening project on the east approach and a new bridge connection adjacent to the existing infrastructure. SR-520 includes both PCC and asphalt; in fact it was the site of a quieter pavement test section from July 2007 to July 2011. The pavement test sections included fresh conventional hot mix asphalt (HMA), new rubber asphalt open graded friction course pavement (OCFG-AR), and new polymer-modified asphalt open graded friction course pavement (OGFC-SBS) (WSDOT, 2011b). However due to construction since, it is inconclusive as to how much of this pavement was still present during study drives. The Bellevue rural roads included the Lake Hills Connector Road and Richards Road, paved with both PCC and asphalt. The Lake Hills Connector Road is a four lane divided system through a forested wetland, with posted speed 40 mph. Richards Road is four lanes with no separation, through a low density development, with a 35 mph posted limit.

Values for IRI were obtained from the Washington State Pavement Materials Laboratory at 0.1 mile increments for mainline lanes on SR-520, I-90, and I-5. These values are based on 2004 conditions and are the most current measurements available for public review. Although the values are upwards to eight years old, they provide some relative information about the conditions of each road in comparison to each other. Table 5 below summarizes the obtained IRI values for the facilities of interest.

Table 5: 2004 IRI for SR-520, I-90, and I-5 (WSDOT, 2004)

	Clockwise IRI (m/km)				Counterclockwise IRI (m/km)			
Facility	*Mean*	*Standard Deviation*	*Min*	*Max*	*Mean*	*Standard Deviation*	*Min*	*Max*
SR-520	1.85	0.77	0.96	3.68	1.88	1.01	0.79	4.85
I-90	1.8	0.67	0.67	3.10	2.04	0.69	0.95	4.49
I-5	3.55	0.73	2.47	5.38	2.96	0.67	1.86	4.24

The following table, Table 6, lists the thresholds for pavement conditions based on IRI levels, as established by both WSDOT and the Federal Highway Administration (FHWA). These values were listed by WSDOT and FHWA in inches/mile, were converted to meters/km for this table.

Table 6: Pavement roughness classifications by IRI thresholds (WSDOT, 2010)

	WSDOT (m/km)	FHWA (m/km)
Condition	*Threshold*	*Threshold*
Very Good	< 1.50	< 0.95
Good	1.52 – 2.68	0.96 – 1.50
Fair	2.70 – 3.47	1.52 – 1.89
Poor	3.49 – 5.05	1.91 – 2.68
Very Poor	> 5.05	> 2.68

3.5 Procedure

Data collection was conducted from July to September of 2012, during the hours of 10:30am and 2:30pm. This time period was selected to ensure all drivers experienced the same daytime lighting environment and level of service (LOS) regarding traffic flow. There was also no drive conducted in adverse weather conditions.

The study began and ended from the University of Washington in Seattle, WA (Mechanical Engineering Building). Upon arrival the researcher provided the participant with the informed consent form, explained the document, and outlined the study route. Once participants signed the consent form, they were then provided general driving instructions (e.g. obey posted speed, no radio, etc.) aimed at keeping the drives as consistent as possible. Prior to beginning the actual drive, participants were hooked up to the ECG device and allotted time to become familiar with the study vehicle. Before the drive began, a three minute resting heart rate was recorded for a baseline measure. Following the drive, participants filled out a four page survey about their driving behaviors and study drive experience. The entire process took approximately 1.5 to 2 hours to complete for each participant.

3.6 Variables

This study measured and calculated several dependent variables for the independent variables of roadway and participant factors.

3.6.1 Dependent

The dependent variables for this study included the physiological and vehicle kinematic measures. The physiological measures included those recorded through the ECG device. This comprised of recording the electrical activity of the heart, which was then cleaned up and interpreted based on heart rate variability. The individual physiological variables used were heart rate (HR), standard deviation of NN intervals (SDNN), root mean square of successive R-R intervals (RMSSD), the proportion of pairs of successive NNs that differ by more than 50 ms (pNN50), and the ratio of low frequency to high frequency spectrum components (LF/HF). The vehicle kinematic measures were listed in the "3.2.1 Instrumented Vehicle" section; the specific ones used in analysis were vehicle speed, video footage for location benchmarks, and location time stamps.

3.6.2 Independent

There were three independent variables: age, gender, and roadway type. Age was separated into three levels (younger, middle, older), gender into two (male, female), and roadway type was 4 levels: newer freeway road (I-90), older freeway road (I-5), scenic mixed with construction (SR-520), and the rural setting (rural Bellevue, WA). The SR-405 stretch of the drive was excluded from analysis because the distance traveled along it was too short and would thus yield insignificant results.

3.7 Data Reduction and Analysis

Both the ECG data and vehicular measurements required a significant amount of reduction and analysis. This section details how the data sets were synchronized, variables were calculated and transformed, and ECG data was reduced by appropriately amplifying R wave peaks and eliminating artifact.

3.7.1 Segmenting Route

The first step in compiling the data was identifying key benchmarks in the raw ECG data. The video recordings in conjunction with the GPS data were used for this to define the beginning and end locations of the four regions of interest. Based on the time stamps for each of these events for each participant, the corresponding time interval in the ECG data was segmented out. That, in addition to the resting ECG recording, resulted in five unique sets of ECG data per participant which was further used in analysis.

3.7.2 ECG Parameters

As established in the Literature Review section, a time domain analysis was selected as the primary means for analysis as it best captures individual stress events. More specifically the parameters SDNN, RMSSD, and pNN50 were used in analysis. However, heart rate (HR) and the frequency domain parameter LF/HF were also used to verify the findings.

The computer program AcqKnowledge has an HRV analysis tool, which calculated and provided an output of the time in seconds between each R-wave peak for the given ECG data. From this, Excel was used to calculate SDNN, RMSSD, and pNN50 values. SDNN was simply calculated by using the standard deviation function in Excel. A macro was created in calculating RMSSD and pNN50 values. Essentially, the RMSSD macro determined the difference in time between each successive RR interval, summed the square of each of these values, divided the sum by one minus the number of RR intervals for the given series, and finally square rooted this value. The pNN50 macro calculated the difference in time between each successive RR interval, counted the number of times the difference was larger than 50ms, and divided by one minus the total number of RR intervals for the given series.

The HRV analysis tool in AcqKnowledge also provided the output for heart rate in beats per minute (bpm) and LF/HF ratio for each participant's segmented ECG data.

3.7.3 ECG Reduction

Since the participants were operating a vehicle and thus not remaining static, the ECG recordings required some reduction to remove artifacts. This reduction was done using AcqKnowledge. There were two types of reductions that were performed per the Biopac manufacturers: the first for adjusting peaks that were too low or too high for threshold and the second for eliminating artifact between cycles.

The first method used the Waveform Math feature to add or subtract a value to the waveform in order to transform the level of the highlighted waveform. This was useful when the R-peak was not significantly higher than the recordings between peaks or was exaggerated beyond the scope.

The second method used the Equation Generator tool, which would set the highlighted waveform/artifact to zero [baseline]. This was useful in completely eliminating the artifact between R-peaks.

After the necessary reduction was applied to the ECG record, a tachogram of the data was created using the HRV analysis tool. The tachogram was useful in highlighting any artifacts that were not caught in the first round of reduction. This led to an iterative process, in which reduction on the data was done until the tachogram output yielded clean recordings.

3.7.4 Normalizing Data

In certain applications of the data, a normalized set of results were used to compare between group trends.

The ECG data was normalized with each participant's at-rest data, collected just prior to their drive. The at-rest data for each participant was analyzed similarly to each roadway segment's data set; that is heart rate, time domain, and the low to high frequency ratio were calculated for each at rest data set. The normalized variable was then obtained by subtracting the at-rest variable value from the recorded value, respectively for each variable HR, SDNN, RMSSD, pNN50, and LF/HF.

For the kinematic vehicle variables, only speed was normalized. Subtracting the posted speed limit from the recorded value normalized the speed. For I-90 and I-5, the segments had consistent speed limits. However, the rural and SR-520 segments were split into two speed zones. The mean posted speed limit for these two facilities was calculated by weighting the posted speed by the proportion of distance within the segment.

3.8 Inferential Results

The data was compiled and analyzed using R statistical software (ver 2.15.2). This program was also used for analyzing outcome significances and both between and within variable relationships. An analysis of variance (ANOVA), using a mixed-effects model, and analysis of covariance (ANCOVA) was performed.

The analysis was completed on 50 of the 54 participants. Two data sets could not be used due to issues with data processing: one set had a corruption in the vehicular data, rendering it impossible to correlate locations to the ECG file; the other set was unusable because the ECG data file was lost. The other two data sets were omitted because of poor ECG recordings where the R-R intervals could not be extracted: one had too much artifact and the other did not have a strong enough signal.

CHAPTER 4: DATA ANALYSIS AND RESULTS

Analysis for this study was based on descriptive statistics acquired from survey data and inferential results from field measurements. This section explores these results, as well as justifies their significance.

4.1 Descriptive Statistics

Each participant completed a survey following their drive, which queried their driving related demographics, behaviors, perceptions, and study participation experience. This self-reporting provided relevant insights into the participant profiles such as that 21 were single, 25 married, 5 divorced, 2 widowed, and 1 other; 43 had gone through a driver's education training class; in the past five years 7 had been in at least one car crash and 16 had received at least one ticket for a moving violation; 45 kept a fairly regular sleep schedule; 13 used no form of vision correction aids; 4 used hearing aids; 51 owned at least one vehicle; 40 drove at least 5 days a week; and 30 considered it at least somewhat dangerous to drive 16 km/hr (10 mph) over the speed limit.

Furthermore, this survey data endorsed the practicality of the results in this study; participants did not feel their driving behaviors were impacted by the presence of the ECG device. In fact, 39 of the 54 surveyed answered "no effect" to how they felt the ECG device affected their driving behavior, 14 "slightly noticed a difference," one answered "noticeable difference, but not severe," and zero responded with "slightly altered driving."

Figure 9 depicts how participants perceived their stress levels throughout key points in the drive. Subjects were asked to rate their stress on each road segment based on a 3 point

Likert scale from extremely stressful (high) to not stressful (low). The bar plot is stacked to further portray the divergence between the age groups.

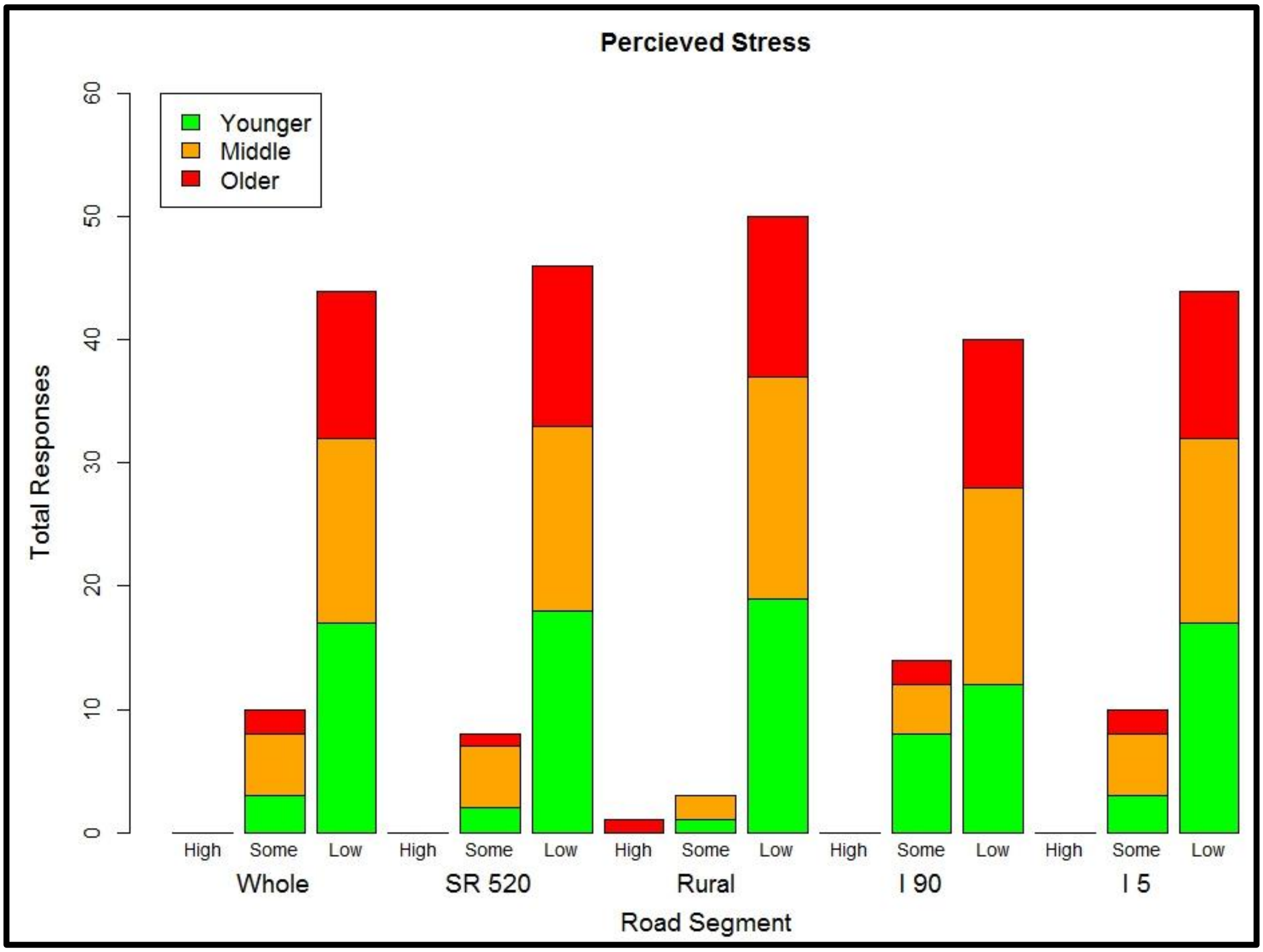

Figure 9: Participant recollection of stress

This plot suggests that the majority of the participants did not feel they were stressed during the drive. However, recorded elevated heart rates and decreased HRV values from their drive suggest differently. This is important because it demonstrates that we cannot rely solely on recalled user memory feedback for examining safety. This is also in conjunction with the extensive research that evaluates the accuracy of memories of past events, which suggests even memories of recent pasts involves a significant blend of fiction and fact (Roediger &

McDermott, 2000). It is also notable that I-90 and I-5 had more responses for the "some stress" category as compared to SR-520 and the rural roads.

The figure below, Figure 10, illustrates the responses to how participants perceived the textural conditions of the road segments on a 5 point Likert scale: from "unbearably bumpy/rough" (1 in the figure) to "uncomfortably bumpy/rough" (2) to "somewhat bumpy/rough" (3), to neither (4), to "enjoyably smooth" (5). Again, the graph breaks the responses into age categories.

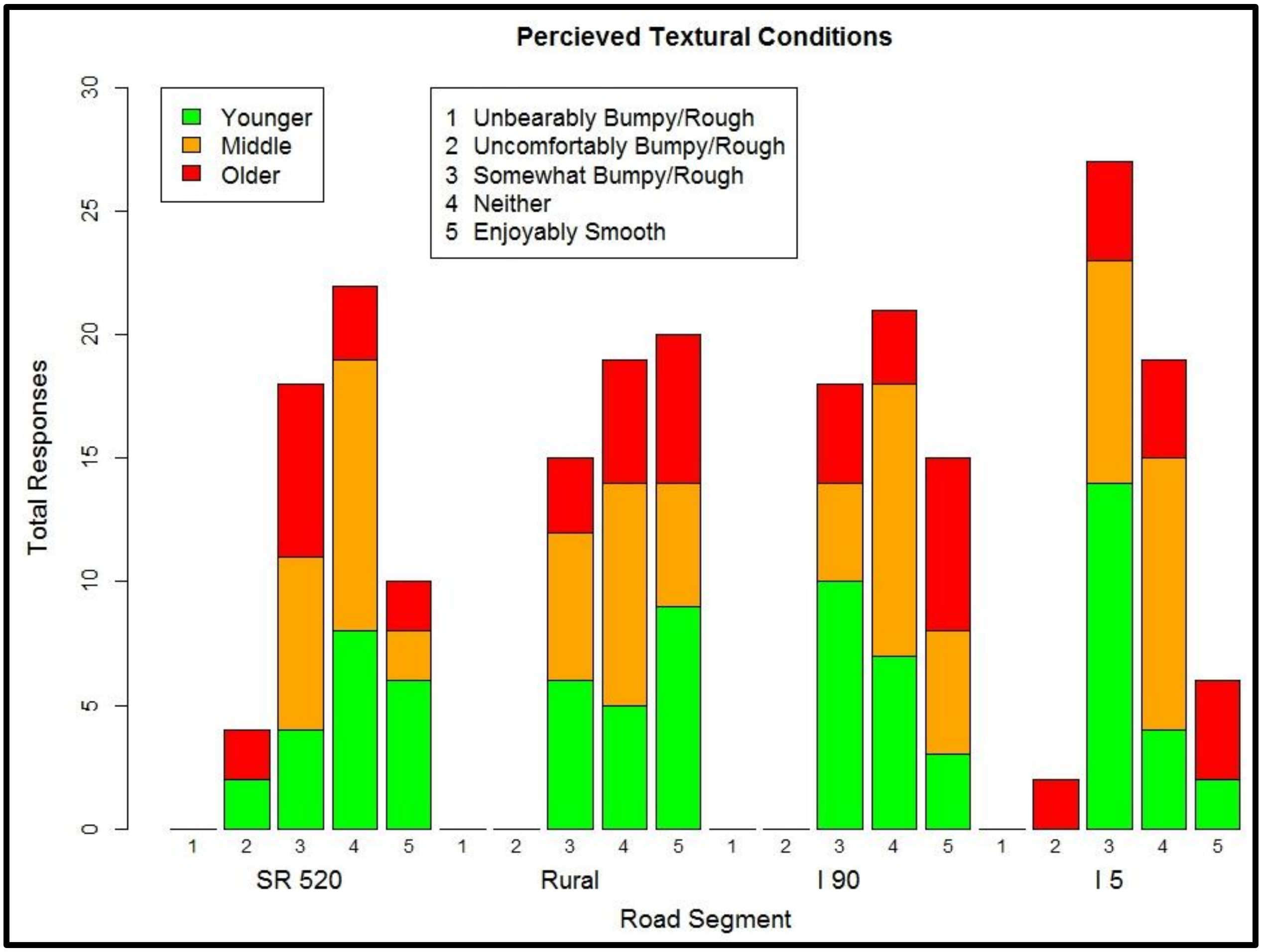

Figure 10: Participant recollection on pavement roughness

The responses indicate that the majority of participants agreed that the rural setting had a smooth ride. It is also significant to note that I-5 was noticeably skewed towards less than ideal conditions more so than the other facilities.

This last figure, Figure 11, summarizes the responses to how participants perceived the visual conditions of the pavement along the segments. The replies varied on a 5 point Likert scale from “unacceptably cracked/rough” (1 in the figure), to “unappealing” (2), to “acceptable” (3), to “appealing” (4) to “nearly flawless” (5).

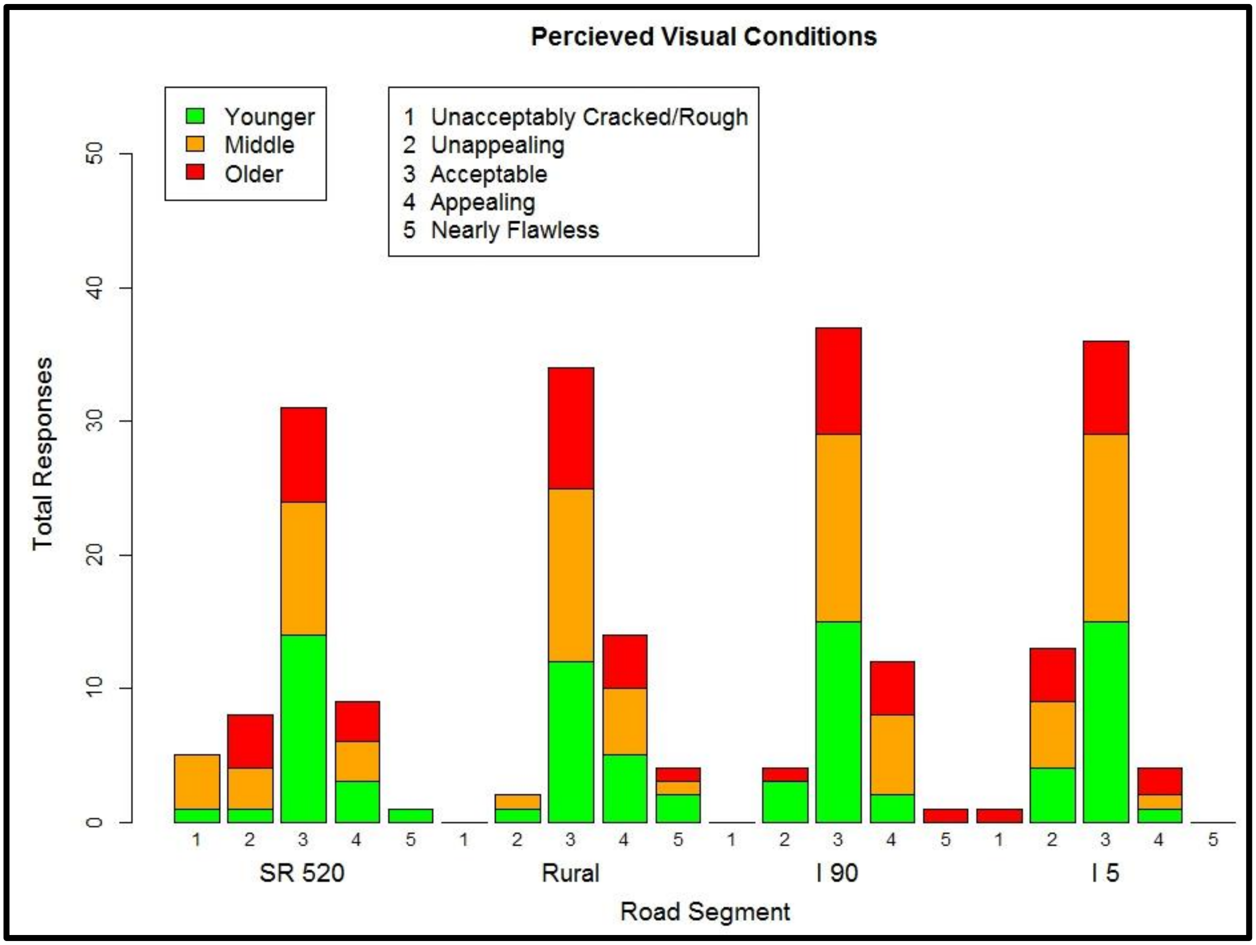

Figure 11: Participant recollection on visual conditions

Responses on the rural setting for these visual conditions are in agreement to those seen above in Figure 10 about textural conditions. It is also again noticeable that I-5 had the largest skew towards less than satisfactory as compared to the other segments. The split between "unappealing" and "appealing" for SR-520 suggests some drivers may have associated a stronger weight on the rough construction segments and the others recalled the smooth scenic aspects of the highway. Literature suggest that personality has a high influence on how people perceive their environment (Kasap, et al., 2009); it also suggests that the mood people felt during a certain event has a significant impact on how they will recollect it as a memory (Snyder & White, 1982). These differences in personalities and associated moods along SR-520 for each participant could explain this split in the survey responses.

4.2 Validating Results

In order to accurately associate and isolate the findings in conjunction with the study objectives, an examination of experimental significance was performed. Success of experimental significance was defined as eliminating external effects on ECG data.

4.2.1 Compiling Directional Data

The initial step in data analysis was to determine if data for inverse trip sets (e.g. clockwise vs. counterclockwise) along the route could be compiled together for a singular HRV analysis. It was important to determine if variables dependent on route direction (e.g. vertical and horizontal alignments) had a significant impact on the ECG data.

For this analysis, short interval SDNN values were calculated for 27 evenly distributed points and one at end point along the route. These points coincided with even one mile increments for distance driven along the route, using 0 to 26.5 miles in the clockwise direction as the base. This is depicted below in Figure 12. The plotted values represent mean SDNN values for each distinct group: clockwise (cw) and counterclockwise (ccw) subjects. The route markers along the x-axis are based on the distance traveled in the clockwise direction.

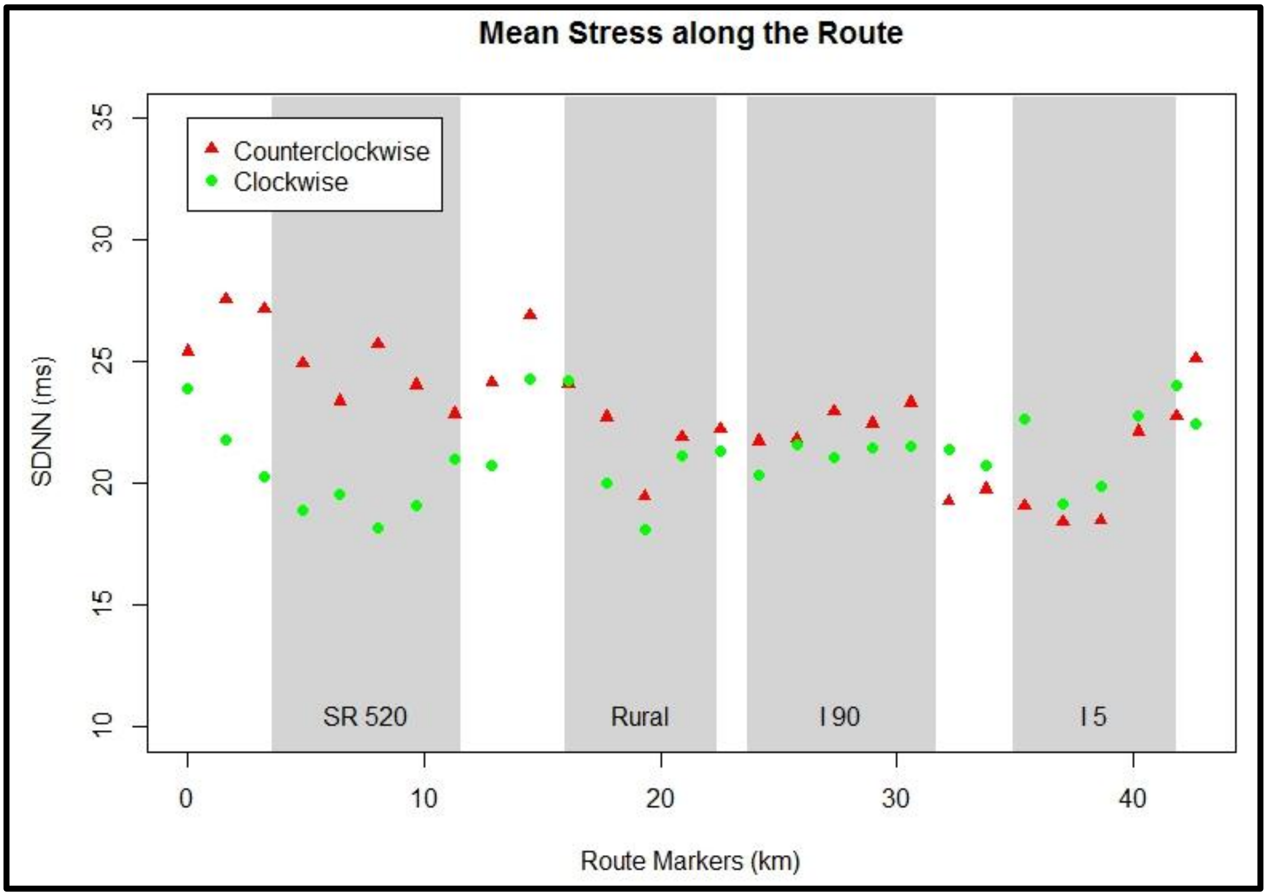

Figure 12: Mean SDNN values versus distance along clockwise route

The actual stress values and relative stress to adjacent points for each direction are very similar for the majority of the route, with exception of the split at the beginning of cw and end of ccw travel. The increased HRV values recorded for ccw movements towards the end of their route could be attributed to driver fatigue (Apparies, et al., 1998). This may also be slightly observed at the end of the cw route just past route marker 30 km, where cw SDNN values measure greater in value than ccw values for the first time along the plot. A closer examination of differing opportunities for resting events (e.g. traffic signals) between the two groups could also explain the larger divergence in HRV values between route markers 0 and 15 km, as HRV recovers after rest (O'Hanlon, 1972).

A 2 (gender) x3 (age group) x2 (direction) x10 (road sequence) mixed analysis of variance (ANOVA) was conducted to further examine the impact of stress (as measured by short interval SDNN), and specifically to examine influences on the split between movements in Figure 1. The findings show that distance driven had a significant impact on stress (F(9,414)=1.903, p=0.05), and specifically, drivers SDNN increased, indicating lower workload and perhaps even more comfort as the study progressed. Hence, this covariate was included to adjust for any experimental effects associated with time in the study.

The outcomes associated with age and gender should now be adjusted accordingly based on the time in the study. The findings showed that age (younger, middle, and older) had a significant effect on stress (F(2,40)=5.023, p=0.011) whereas gender (F(1,40)=0.100, p=0.753 and the interaction of age and gender did not (F(2,40)=2.210, p=0.123). Direction of travel was also not significant (F(1,40)=0.682, p=0.414).

A more specific look at SDNN values at the individual level indicates that an outlier in the counterclockwise cohort could also be attributed to the higher values for mean counterclockwise travel as compared to mean clockwise SDNN values (Figure 13). The solid lines, representing group means, allow for a comparison of relative stress to contiguous locations.

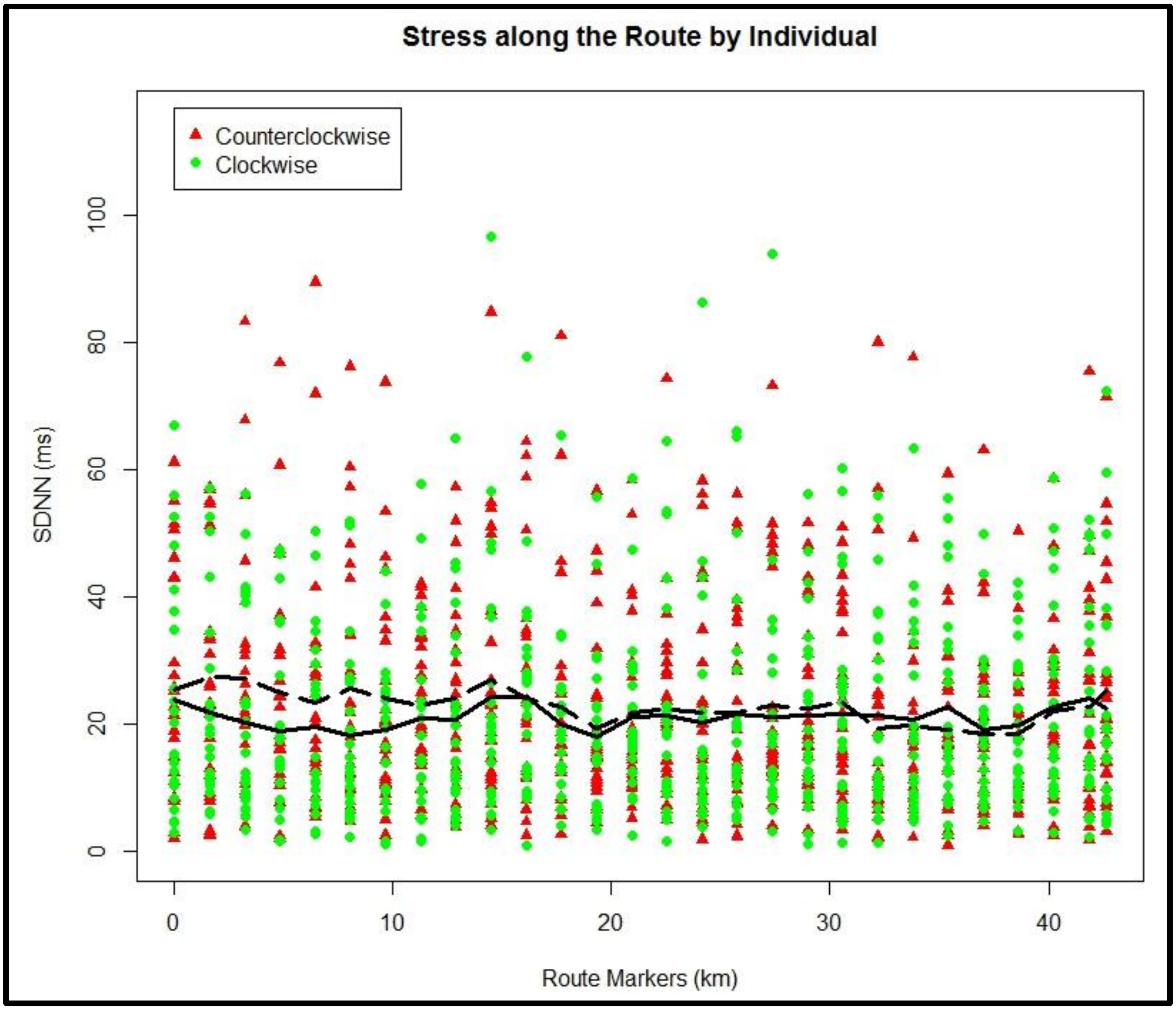

Figure 13: SDNN values by the individual along the route

The areas of interest (at rest, SR-520, Rural, I-90, and I-5) have been extracted and displayed in Figure 14, for parameters of heart rate, frequency domain LF/HF, and time domain SDNN. These values are based on relatively long interval ECG data as compared to the short interval data from Figure 12 and Figure 13. The plots provided in Figure 14 allow for a comparison of stress experienced across each pavement type between the two groups, where cw is represented by the solid line and ccw the dashed line.

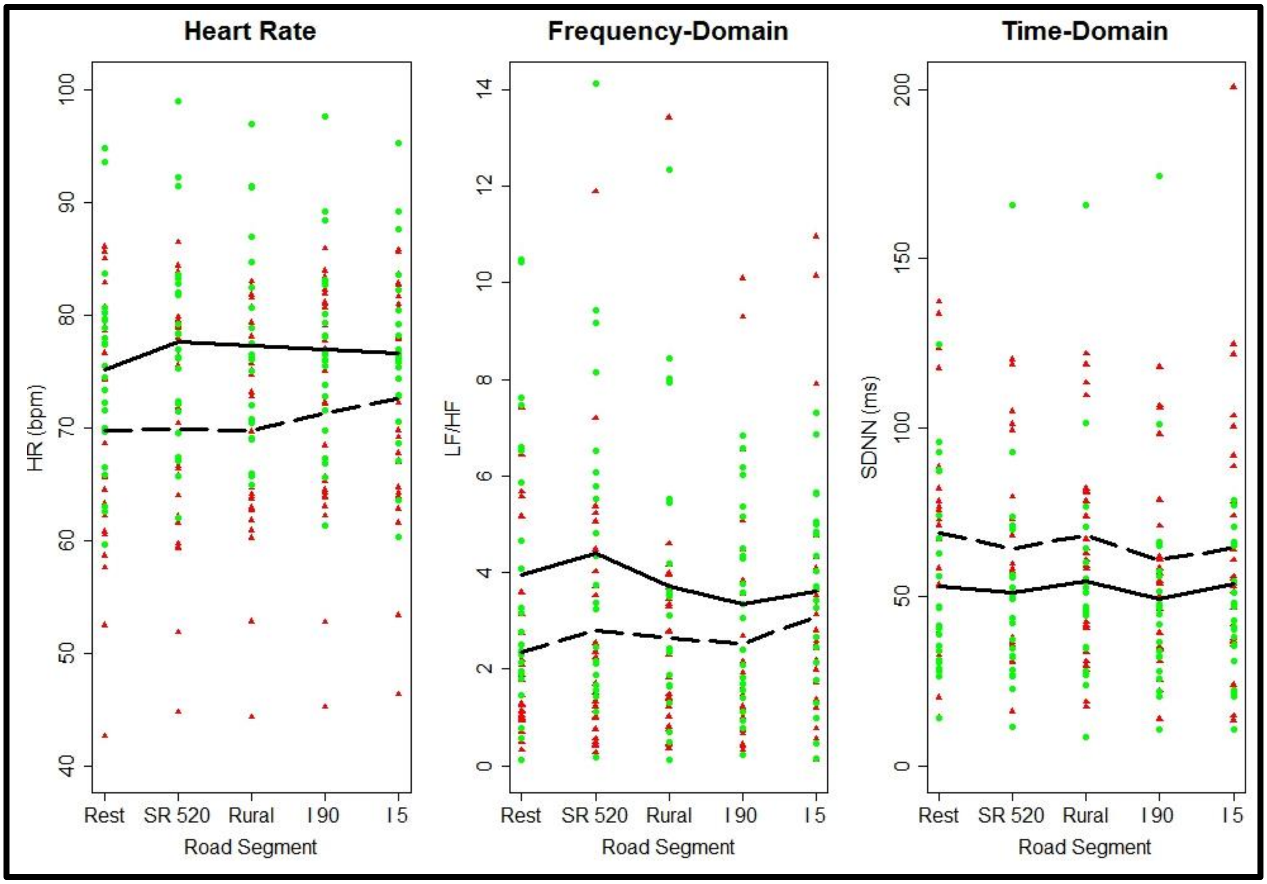

Figure 14: Comparison of mean HRV parameters

Theoretically and based on past studies, heart rate (beats per minutes) and the frequency domain values (LF/HF) should be similar, while the time-domain should be inversely related to heart rate and LF/HF. The incremental changes over the drive in a specific direction are expected to also vary in the same manner. Findings from this study indicate comparable incremental changes between the time (SDNN) and frequency (LF/HF) parameters. This is easily noticed by comparing peak high points in LF/HF to peak low points in SDNN. Conversely, the values for mean heart rate appear to coincide more with distance traveled rather than surface conditions. This can be noted by the steady decline in heart rate as distance progresses (e.g. the clockwise group has a spike in heart rate at the beginning of their drive (SR-520) and slowly decreases; the counterclockwise group also has a similar trend, with a peak heart rate along their first facility (I-5) and has decreasing values from there on). There are also similarities between heart rate and the LF/HF ratio; increases and decreases of relative stress detectable in the LF/HF plot are also visible, though less distinct, in the heart rate plot.

Although there is a slight gap between mean values for the clockwise and counterclockwise groups, the overall progression of relative stress and incremental changes are comparable for SDNN and LF/HF variables. The crests for high and low levels of stress for these two parameters are mirrored between their respective clockwise and counterclockwise movements.

These variables (HR, LF/HF, and SDNN) were further tested between cw and ccw movements for each of the four roadways of interest (Table 7). HR and LF/HF were normalized by each participant’s resting value for the respective parameter. SDNN was standardized by dividing the standard deviation of interbeat-intervals (SDNN) by the average interbeat-interval (Brookhuis & De Waard, 2001). Note these values correspond to relatively long duration intervals (approximately 5 minutes). Similarly to the results extracted from the plots in Figure 14, there were insignificant differences between direction of travel for LF/HF and SDNN values along the segments. The comparison of heart rate values between directions of travel also showed no significant difference, with the exception of borderline significance for SR-520. Otherwise, all p-values indicated comparable responses between the two directions of travel.

Table 7: Difference between cw and ccw directions of travel

Variable	SR-520	Rural	I-90	I-5
Normalized HR	t(47.1) = 1.910 p-value = 0.062	t(43.3) = 1.519 p-value = 0.136	t(47.6) = 0.120 p-value = 0.905	t(42.9) = -1.227 p-value = 0.227
Normalized LF/HF	t(39.4) = -0.002 p-value = 0.998	t(47.9) = -0.782 p-value = 0.438	t(47.7) = -1.329 p-value = 0.190	t(44.1) = -1.467 p-value = 0.149
Standardized SDNN	t(48.0) = -1.155 p-value = 0.254	t(48.0) = -0.653 p-value = 0.517	t(47.9) = -0.863 p-value = 0.393	t(47.9) = -0.863 p-value = 0.393

The geometric configurations (e.g. vertical and horizontal profiles) and temporal factors (e.g. traffic and lighting) encountered by drivers in the clockwise and counterclockwise directions were almost identical. Therefore by Shankar and Mannering (1998), effects from endogenous variables (e.g., speed and alignments on an interstate, regardless of direction was the same) are similar and can be examined together. In general, the values for heart rate variability parameters (SDNN and LF/HF) were consistent with one another for examining participants stress levels; LF/HF values increased for decreasing SDNN and vice versa. This implied that for points of high LF/HF coupled with low SDNN values, participant's experienced elevated stress (Miyaji, et al., 2010). The slight discrepancies may be attributed to a slightly unbalanced design (with a few more older drivers in the counterclockwise direction than clockwise). As noted in the ANOVA, differences in age did impact SDNN. This impact from age justified further analysis of HRV parameters between subjects by age. On the whole, all parameters (HR, LF/HF, and SDNN), when normalized showed similar outcomes between clockwise and counterclockwise movements. Therefore it is reasonable to combine data sets for the two groups (cw and ccw) and all subsequent analysis does not consider direction of travel relevant.

4.2.2 Driving Speeds

The last significant external variable to eliminate as having an impact between groups was driving speed. Although participants were told to obey the posted limit, it is important to verify that this was followed.

The measured speeds, normalized by posted speed limit, on each facility by age group are shown below in Figure 15. The plotted speed represents the mean speed for each individual along the segment of interest. In this figure, a negative normalized speed corresponds to driving below the posted speed limit, and a positive speed coincides with exceeding the posted limit. As discussed above in the Segment Characteristics section (Section 3.4), SR-520 and the rural roads have a change in posted speeds through the study route. For these sections, the assumed posted speed limit was calculated based on a ratio of the distance for each posted limit to the total distance along the segment.

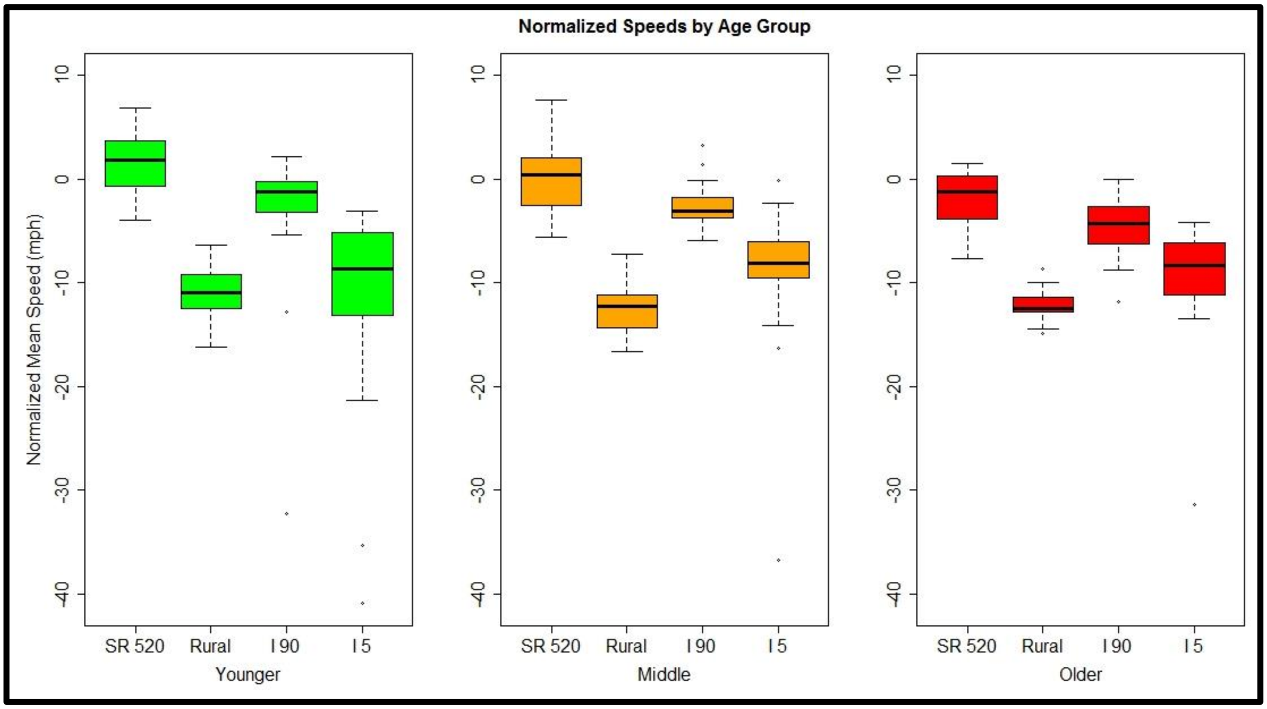

Figure 15: Normalized speeds

No participant had a mean speed exceeding the post speed limit by more than 10 mph. Each group has some outliers on I-5, indicating a few experienced some traffic congestion. As expected there is a slight difference in speed between each roadway segment, however this pattern is visible across all age groups. Also, the variations in mean speeds within each age group are comparable to the variations observed between age groups.

A mixed analysis of variance (ANOVA) was conducted to examine the impact of speed on road type, age group, and gender, with interaction effects included. Road type was a within subject variable, while age group and gender were between subject variables (Table 8).

Table 8: ANOVA for normalized speeds

Variable	numDF	denDF	F-value	p-value
(Intercept)	1	156	212.179	<0.0001
Road Type	3	156	71.059	<0.0001
Age Group	2	47	0.605	0.550 (ns)
Gender	1	47	3.749	0.059 (ns)
Age Group: Gender	2	47	0.195	0.823 (ns)

Note: (ns) indicates not significant

A similar but more specific analysis was also run to verify that no single specific group had outlying speed data (Table 9). To do this, dummy variables were assigned to groups with potentially biased data. Based on observations, this included the younger male, older female and older male groups.

Table 9: ANOVA for measured speeds using dummy variables

Variable	numDF	denDF	F-value	p-value
(Intercept)	1	156	205.972	<0.0001
Road Type	3	156	71.759	<0.0001
Young Male	1	49	2.319	0.134 (ns)
Old Male	1	49	0.094	0.760 (ns)
Old Female	1	49	0.797	0.376 (ns)

Based on the p-values from Table 8 and Table 9, the road itself has significance on the speed, while age and gender do not. Therefore it is appropriate to assume that speed effects will not affect between subject comparisons.

4.3 Transformations

Several studies that report heart rate variability results using frequency domain parameters log transform the low to high frequency ratio (Kobayashi, et al., 2012; Tarkiainen, et al., 2005). Kobayashi et al (2012) reported that transforming this ratio produced the best improvement on the skewness and kurtosis. For this study, the LF/HF values for each participant along each segment were tested for normality to determine whether the skew indicated the need for a transformation of the distribution (Figure 16), as suggested by these previous studies.

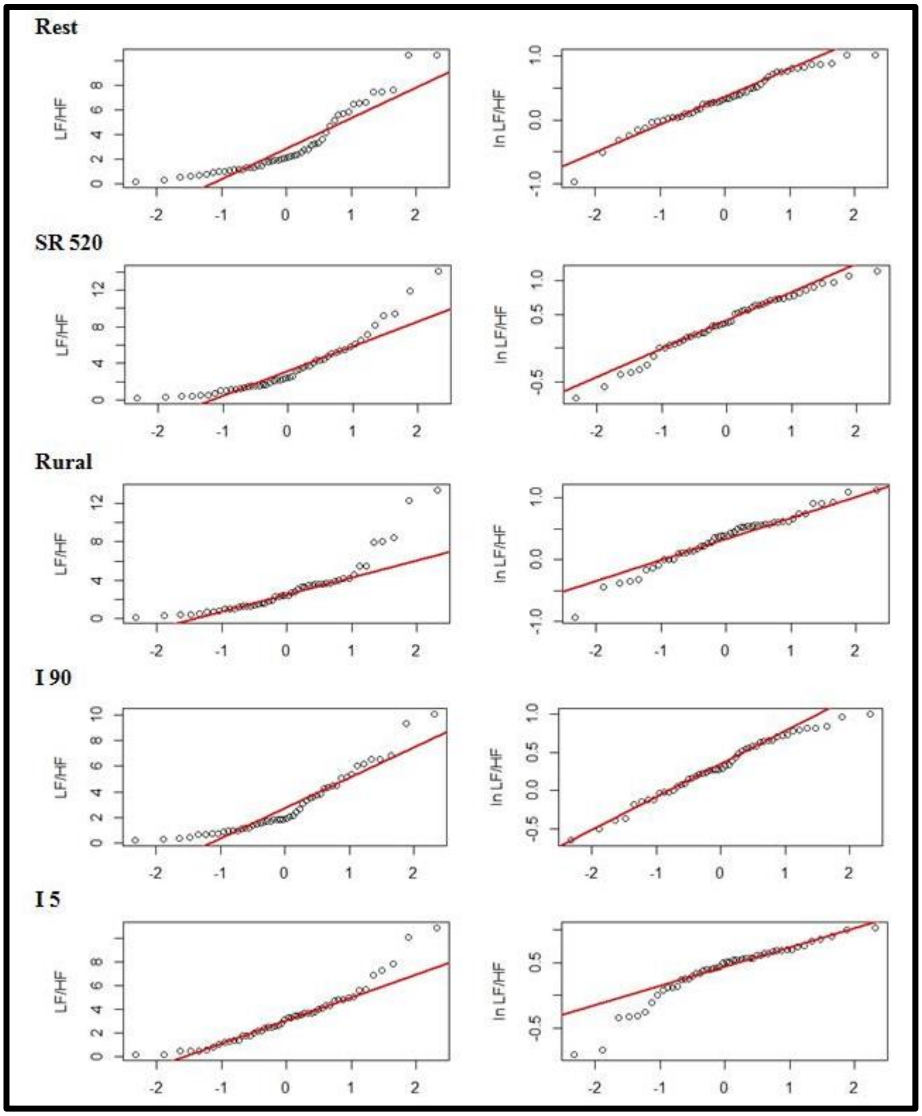

Figure 16: Natural log transformation of LF/HF

It is apparent from the graphs that the natural log transformations of the data have the least departure from the normal line. Therefore all subsequent analysis using this frequency domain parameter utilizes the natural logarithmic transformation.

4.4 Dimensions of Stress

A closer examination of each HRV parameter within the four facilities and at rest can be used to compare relative stress levels between these five situations. Furthermore, trends between different groups (e.g. age and gender) can assist in understanding how noteworthy user groups react to various roadway conditions. Note, as explained in the literature review, increases in stress coincide with increases in heart rate and the low to high frequency ratio, but decreases in SDNN, RMSSD, and pNN50 parameters.

4.4.1 Gender Effects

A comparison of the ranges for heart rates and SDNN values between genders is provided in Figure 17. In both cases (heart rate and SDNN), males demonstrated greater variability. However, the relative stresses among females and males between each of the facilities are comparable, and validated between parameters. This can be noted through the mean bar within each box as compared to the means of other facilities. Specifically, rural is notably less stressful for all groups while I-90 reflects highest stress.

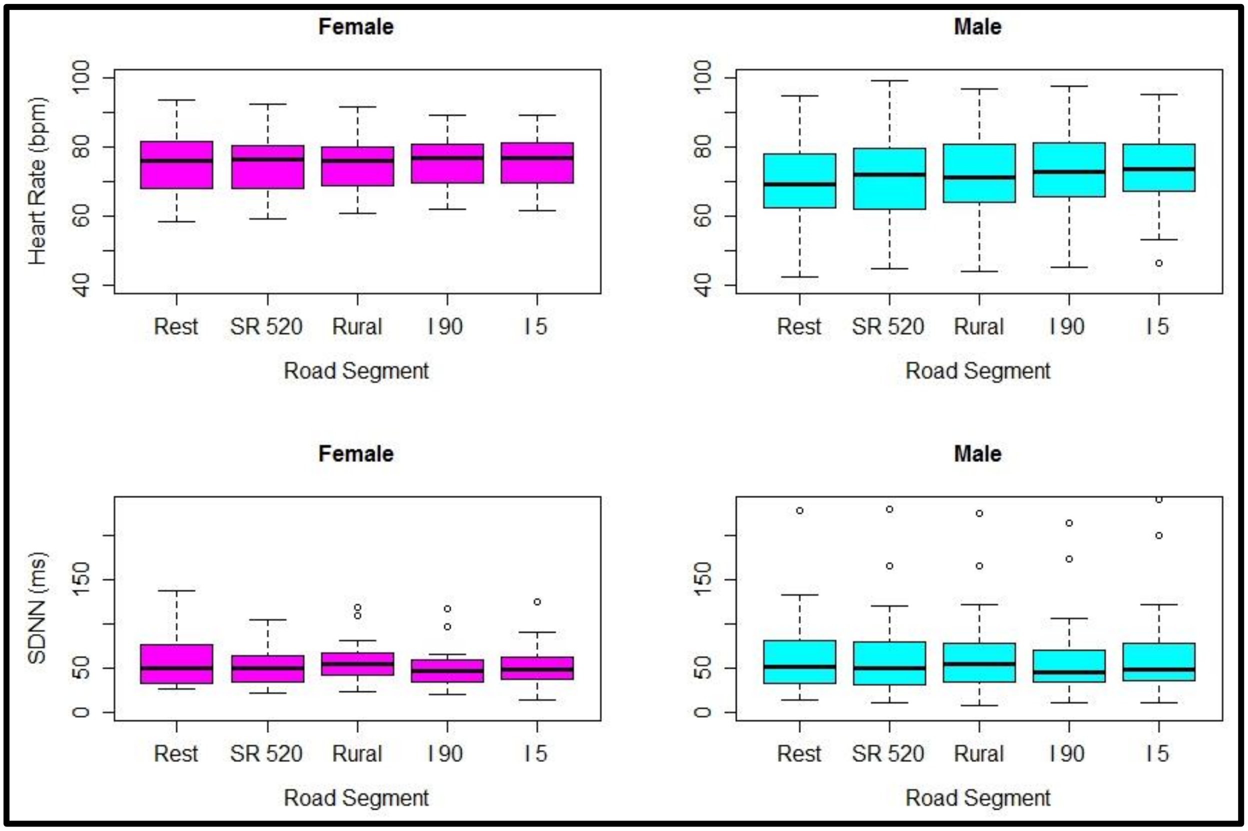

Figure 17: Between genders stress comparison

4.4.2 Age Effects

In a comparison across ages (Figure 18), it is apparent that similar stress effects induced by roadway conditions were seen between each age group for corresponding facilities. The means for each age group were consistently varied in heart rate; however the standard deviation in SDNN for younger and middle aged was much smaller as compared to that of the older group. For example, once again rural consistently ranks low on measured stress.

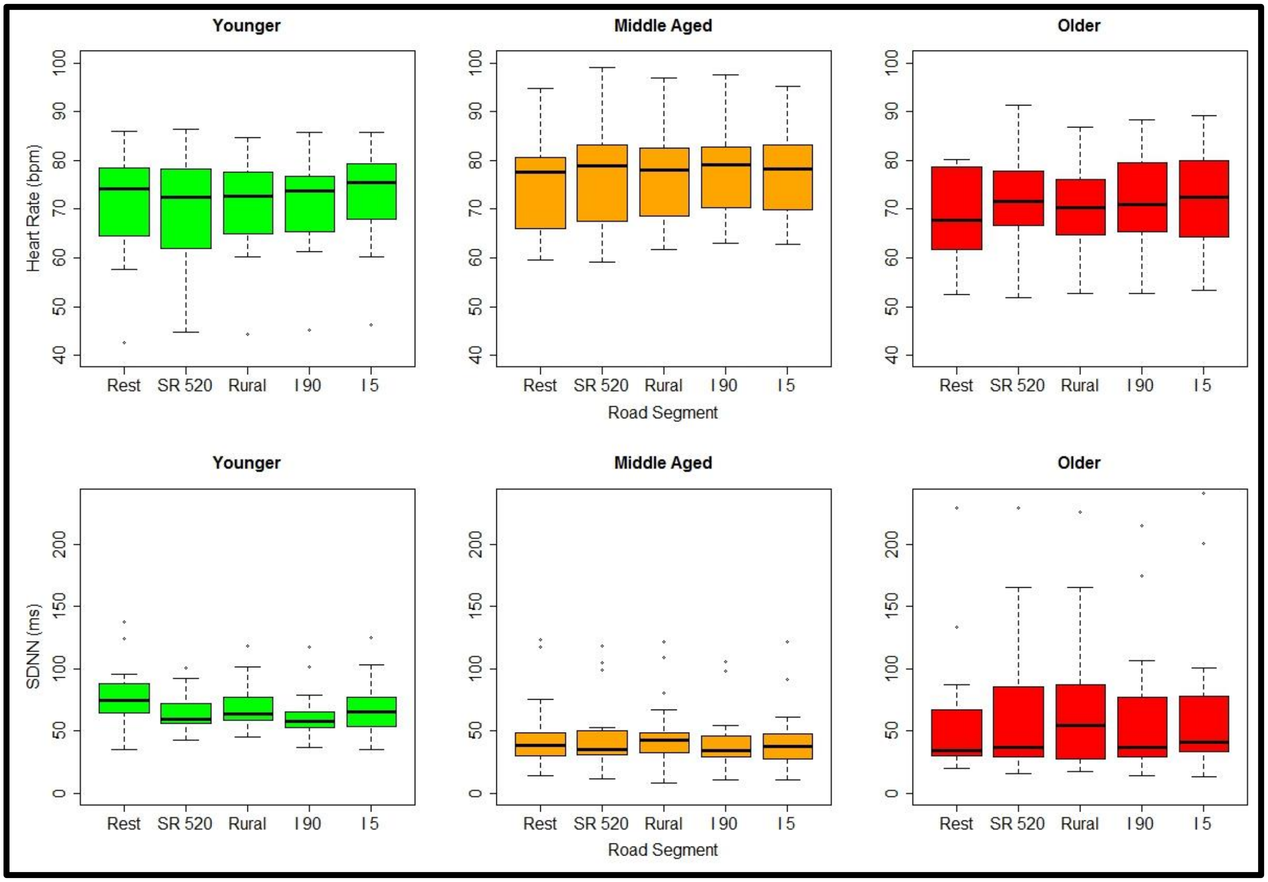

Figure 18: Between age groups

4.4.3 Comparing Group Mean Heart Rate Values

A plot of the mean heart rate and normalized heart rate values by group has been provided below in Figure 19. This figure shows identical trends in relative stresses between the facilities within each age group. However, the normalized plot emphasizes the changes in stress induced by each facility as compared to the resting state.

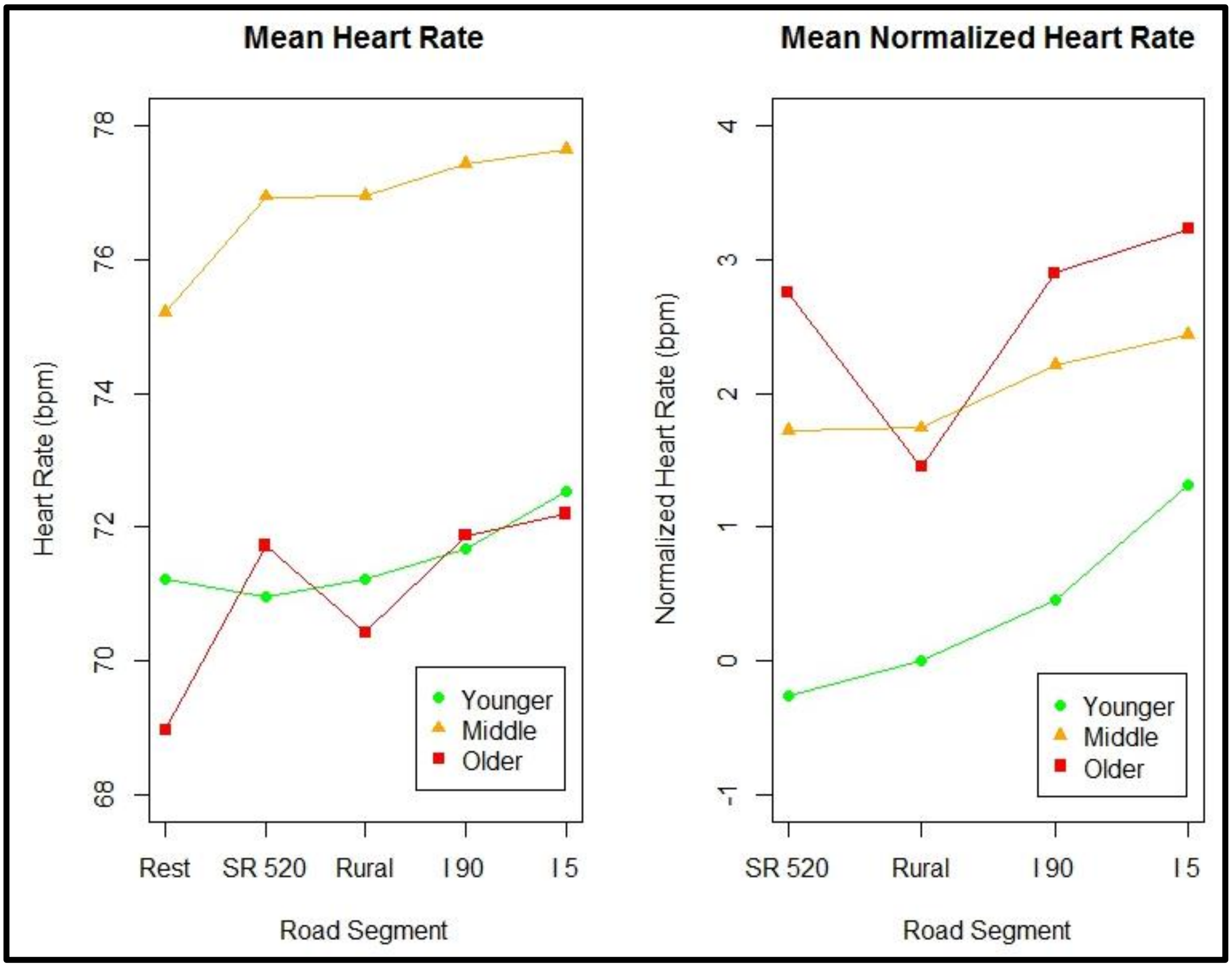

Figure 19: Mean heart rates between age groups

In each plot general trends were mirrored across each age group but varied in degree of extremity. The most stress was observed along I-5, followed by I-90 for all age groups. Additionally, each age group found SR-520 and the rural roads least stressful. Moreover, the normalized heart rate plot highlights the fact that driving induced stress to all age groups on all road segments, except for the younger age group along SR-520.

A similar comparison, but looking at groups by gender is provided in Figure 20. In this graphic, increased stress was observed under all road segments, except for females on the rural roads. Similarly to the plots from above, there was a noticeable elevation in stress along I-5 and I-90 as compared to the lowered stress measured in SR-520 and the rural roads. The trends between male and female groups are reflective of each other, signifying that both genders are equally affected by the roadway conditions.

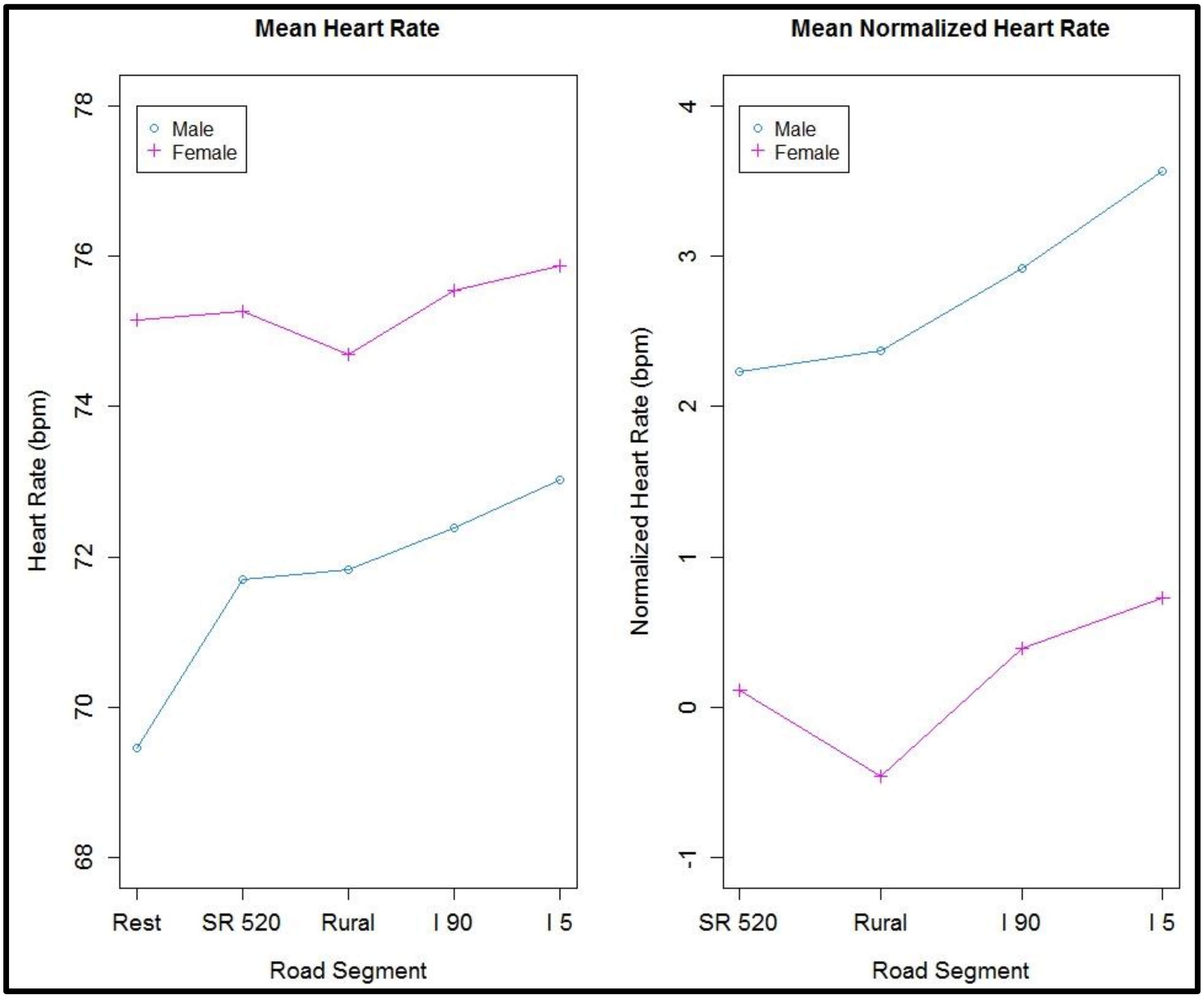

Figure 20: Mean heart rates between genders

The figures from this section indicate that the same results can be obtained from comparing mean heart rates and mean normalized heart rates.

4.4.4 Group Mean SDNN Values

By evaluating SDNN values (Figure 21and Figure 22), similar observations of stress can be inferred. Note: SDNN values decrease for increasing stress. Negative values on the normalized scale correspond to an increase in stress as compared to the resting state.

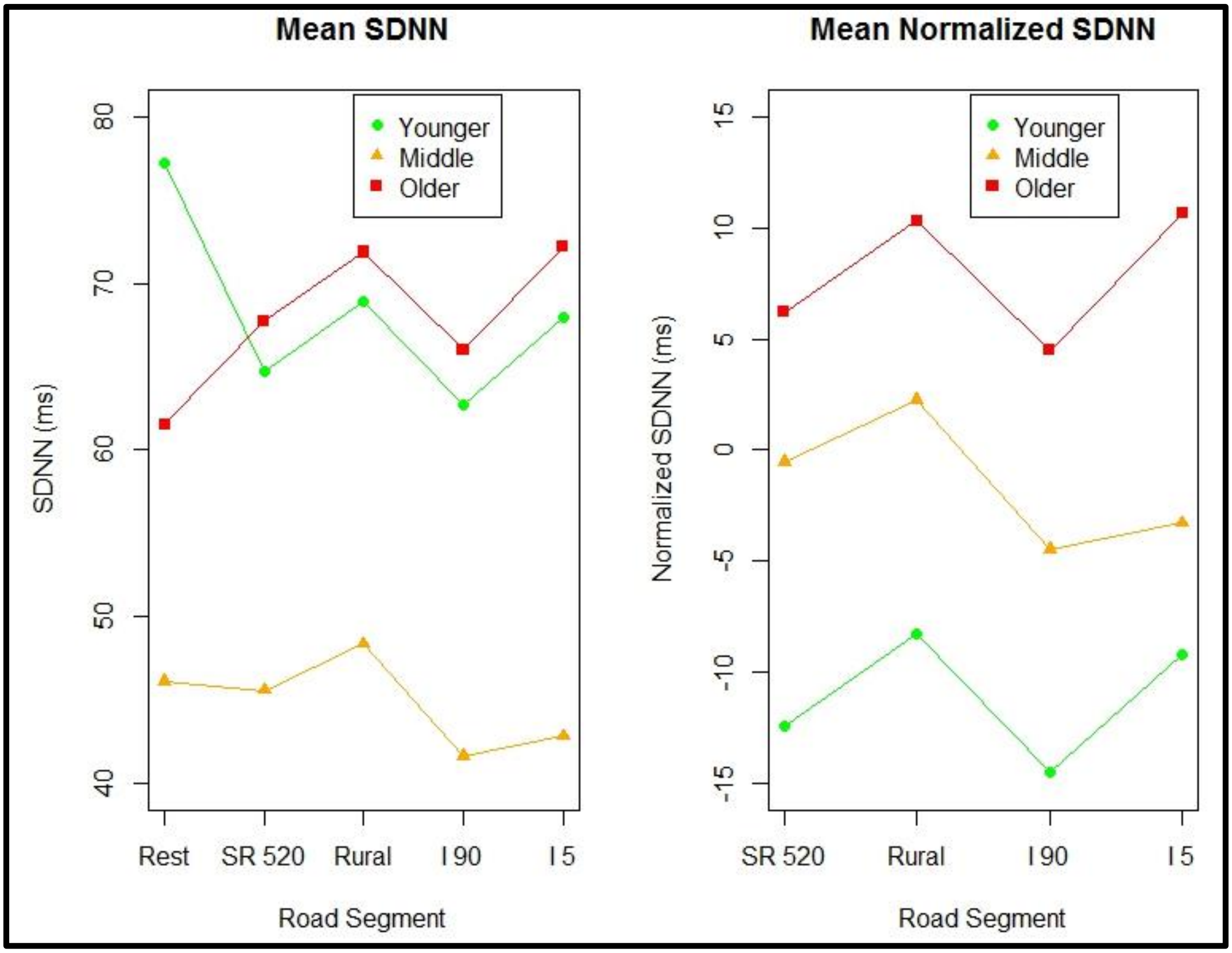

Figure 21: SDNN values between age groups

The younger group felt the least amount of stress on the rural roads, followed closely by I-5, higher stress on SR-520, and the most elevated stress on I-90. The middle age group had peak high stress on I-90 trailed by I-5, lower along SR-520, and the least along rural. The older group shadowed the younger group for relative stresses. However, the older group was the only group to record stress levels consistently lower during driving as compared to at rest.

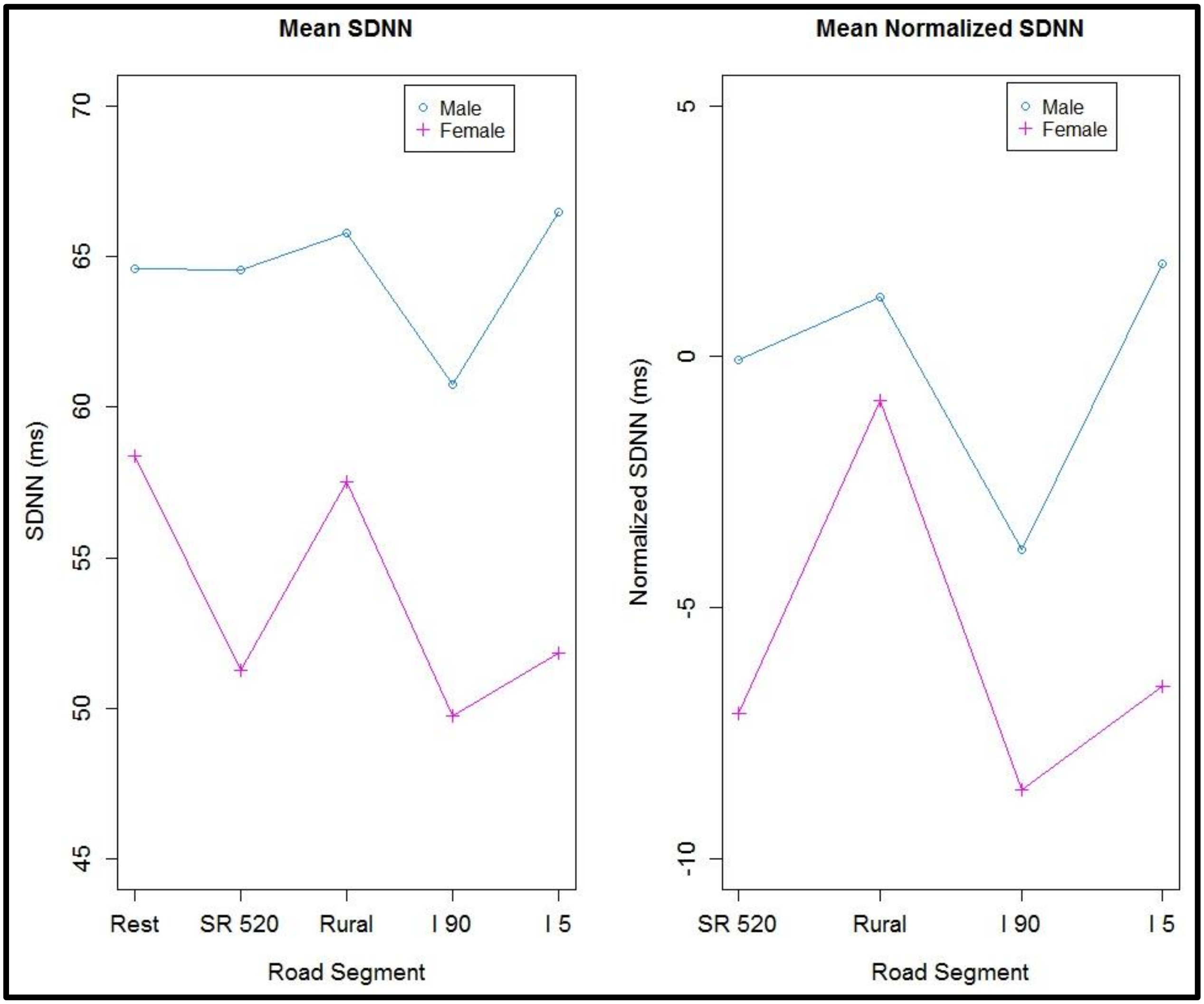

Figure 22: Mean SDNN values between genders

As similar to that found in comparing heart rate recordings, male and female groups experienced the same shifts in stress levels. The SDNN values for genders across road segments also coincide with the trends observed in the other figures.

4.4.5 Comparison of Between Parameter Results

The previous sections have indicated that similar effects are seen across different ages and genders, although degrees of the effects do differ across the groups. Figure 23 examines the consistencies amongst common heart rate variability parameters: time-domain SDNN, RMSSD, pNN50, and frequency-domain log transformed LF/HF.

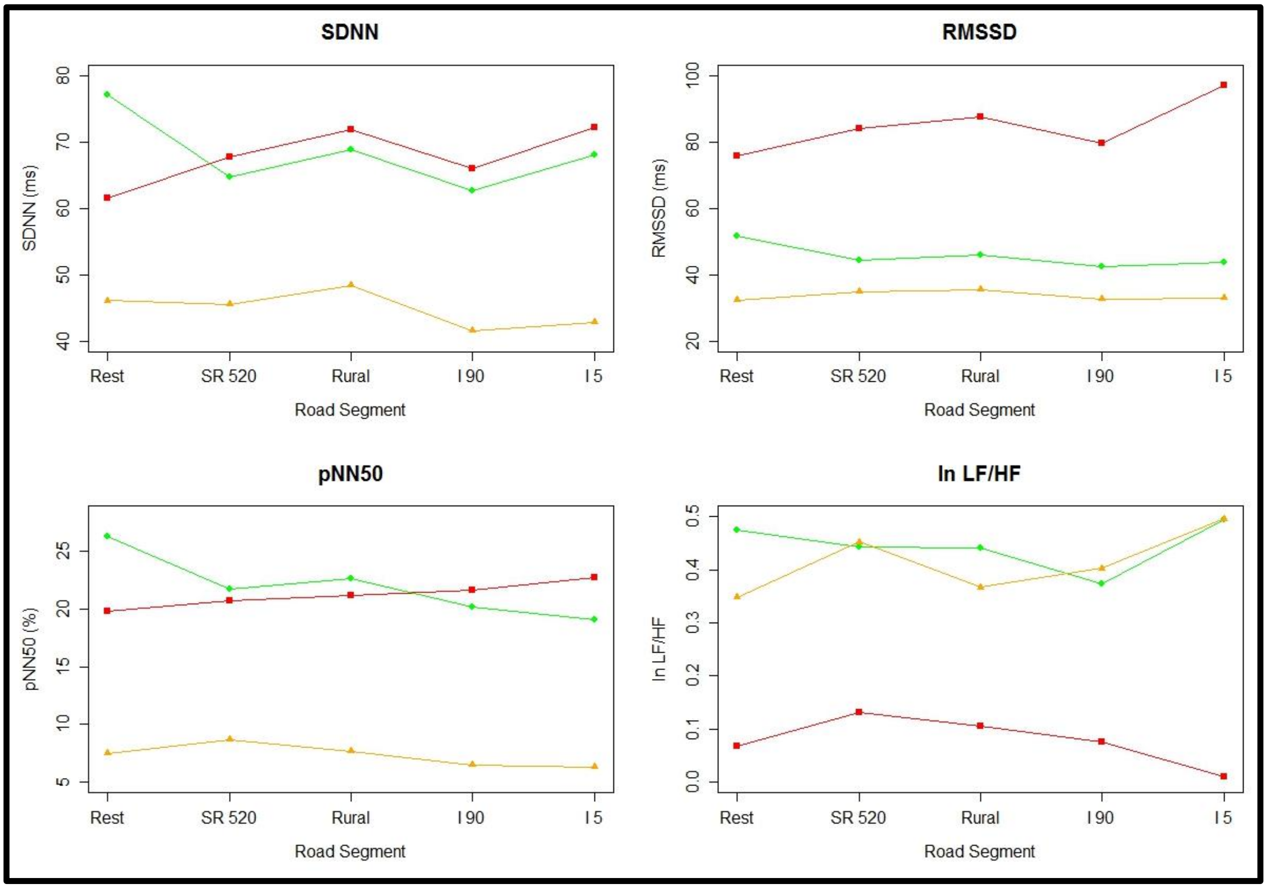

Figure 23: Comparison of parameters by age

Time domain parameters for the three age groups are all fairly consistent with each other, although RMSSD and pNN50 values between different road segments show the least contrast as compared to SDNN, which is more dynamic.

The LF/HF ratio calculated across these facilities does not appear to be consistent with the other parameters. This is the only parameter where the three age groups do not follow general trends with one another. These discrepancies could be attributed to the nature of the LF/HF ratio; time-domain parameters are able to highlight acute stress events, while frequency-domain parameters often abate the acute stress experienced from driving (Tarkiainen, et al., 2005). Studies have also found the highest variability in these frequency domain parameters (Kuss, et al., 2008). Another limitation in interpreting the LF/HF ratio resides in understanding which frequency band (high or low) is acting or responding. Some literature suggests that it is a strong indicator of sympathetic modulation (Montano, et al., 1994; Malliani, et al., 1991), while others consider it to reflect both sympathetic and parasympathetic inflections (Appel, et al., 1989; Harris & Matthews, 2004). Therefore, a more accurate application of the LF/HF ratio would include looking at the actual values of low frequency and high frequency within each subject.

For all parameters, the older age group had recorded values corresponding to the highest experienced stress relative to the younger and middle age groups. This is also very evident in Figure 19 and Figure 21 (the normalized plots). This is expected, as literature suggests older drivers are highly susceptible to stressed induced by driving, especially situation specific stress (Westerman & Haigney, 2000).

A more specific look at the actual mean values used for these parameter plots has been provided in Table 10. Although many values have a relatively large standard deviation, a similar table for the normalized values would show more stability. This could account for some of the inconsistency across parameters in Figure 23.

Table 10: HRV Parameters

		Rest	**SR-520**	**Rural**	**I-90**	**I-5**
HRV Parameter	**Age Group**	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*
HR (bpm)						
	Younger	71.21 (11.19)	70.95 (9.57)	71.22 (10.36)	71.66 (9.67)	72.53 (9.79)
	Middle	75.21 (10.26)	76.93 (8.26)	76.95 (10.46)	77.42 (8.97)	77.65 (10.26)
	Older	68.97 (9.41)	71.72 (10.16)	70.42 (9.70)	71.87 (9.87)	72.20 (9.22)
SDNN (ms)						
	Younger	77.19 (24.71)	64.75 (21.17)	68.92 (15.23)	62.67 (19.19)	67.99 (18.28)
	Middle	46.09 (29.90)	45.55 (26.43)	48.36 (29.40)	41.61 (23.79)	42.82 (28.43)
	Older	61.54 (61.84)	67.75 (73.12)	71.87 (67.80)	66.04 (64.98)	72.19 (64.53)
RMSSD (ms)						
	Younger	51.74 (21.21)	44.28 (16.98)	45.81 (16.99)	42.58 (16.49)	43.70 (16.62)
	Middle	32.32 (40.48)	34.84 (43.23)	35.44 (38.62)	32.68 (35.83)	32.96 (40.79)
	Older	75.87 (105.94)	84.02 (128.93)	87.62 (115.89)	79.77 (110.54)	97.20 (111.29)
pNN50 (%)						
	Younger	26.26 (13.73)	21.73 (12.56)	22.61 (14.11)	20.16 (11.61)	19.11 (12.63)
	Middle	7.48 (13.84)	8.68 (11.66)	7.69 (16.64)	6.49 (12.66)	6.30 (12.97)
	Older	19.78 (28.86)	20.72 (32.75)	21.19 (31.34)	21.64 (32.87)	22.75 (31.83)
ln LF/HF						
	Younger	0.47 (0.32)	0.44 (0.27)	0.44 (0.33)	0.37 (0.32)	0.50 (0.31)
	Middle	0.35 (0.36)	0.45 (0.36)	0.37 (0.41)	0.40 (0.39)	0.50 (0.33)
	Older	0.07 (0.50)	0.13 (0.51)	0.11 (0.54)	0.08 (0.42)	0.01 (0.58)

As expected, there is a significant difference between the variations in the younger and middle groups in comparison to the older group. Furthermore, the large standard errors may account for insignificant results found in the analyses of variance.

4.4 Stress and IRI

The pavement conditions based on reported 2004 IRI values for each of the three highway facilities within this study are plotted versus category thresholds in Figure 24, Figure 25, and Figure 26. The lane miles along the x-axis represent distance along the facility, with lane mile 0 representing the beginning of the segment within the study. Note these thresholds correspond to WSDOT standards.

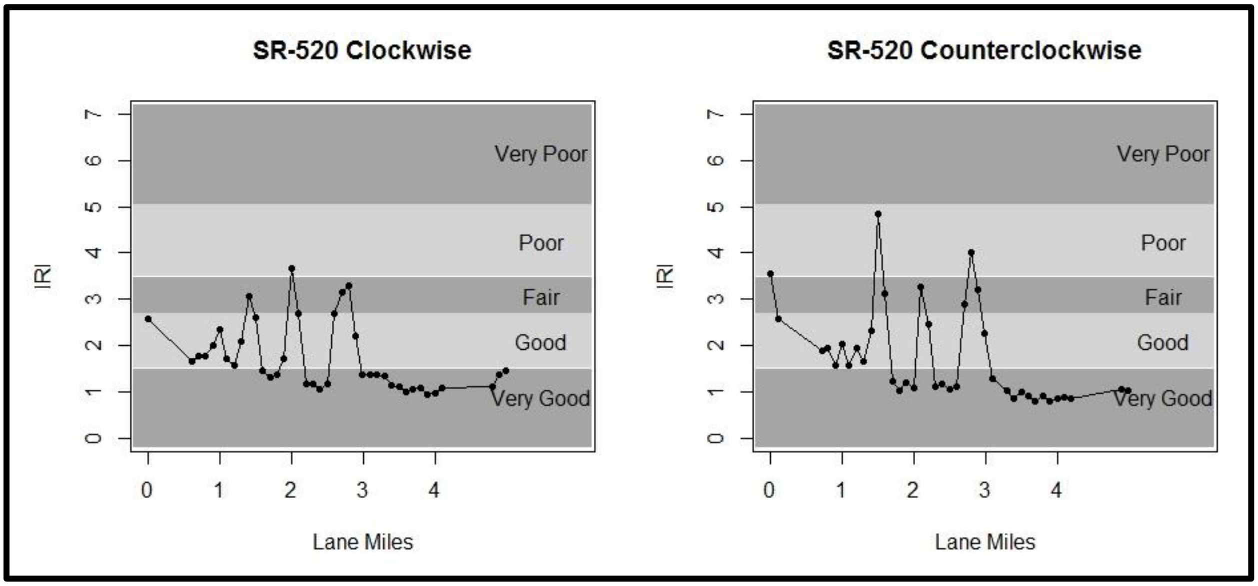

Figure 24: SR-520 IRI values

The two directions along SR-520 are very similar, with pavement surfaces favoring "good" conditions, though with substantial variation.

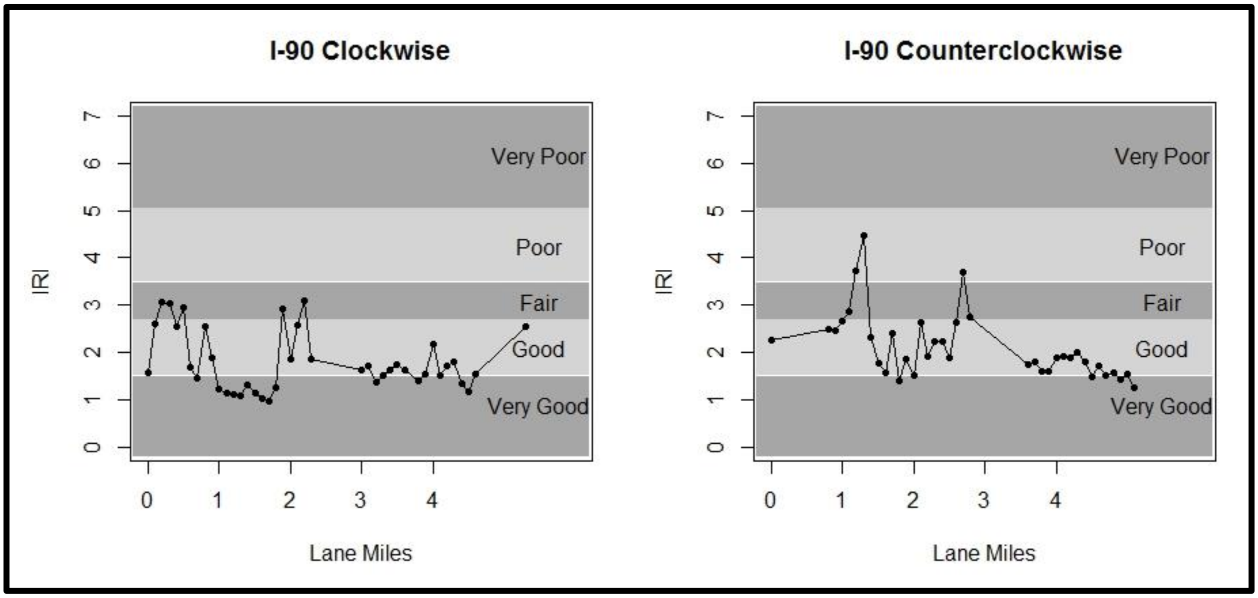

Figure 25: I-90 IRI values

Both directions on I-90 had pavement surfaces considered in “good” condition.

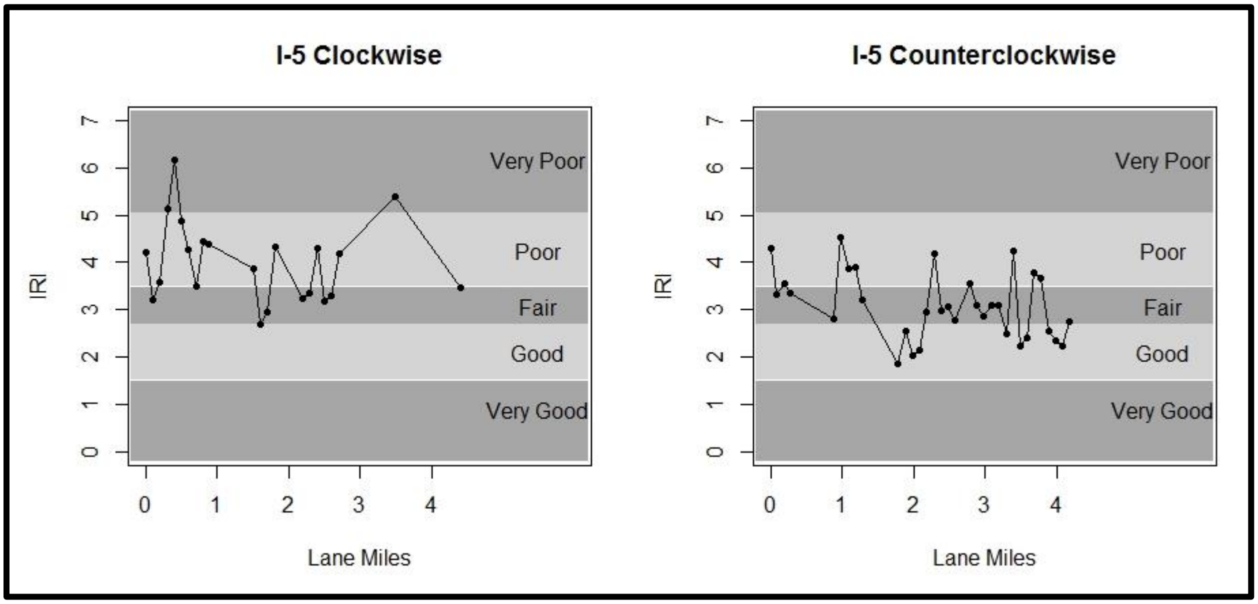

Figure 26: I-5 IRI values

The I-5 clockwise roughness is best categorized by “poor”, whereas the counterclockwise varied in and out of “fair.”

Although only historical values of IRI are available for these segments, an analysis of the covariance between measured stress and these IRI values for each segment could provide initial insights for future research. However, as the time interval on a selected ECG waveform shortens, the HRV parameter becomes more unstable. In order to maintain credible HRV output, the road segments could not be fragmented enough to compile enough data points. The test on each road for covariance between IRI and stress did not yield significant results. It was surmised that IRI may have been correlated with heart rate variables. There was not a strong correlation observed for the four roads examined in this study (see Figure 27). For example, a correlation coefficient (r) would be near 0 for all road types.

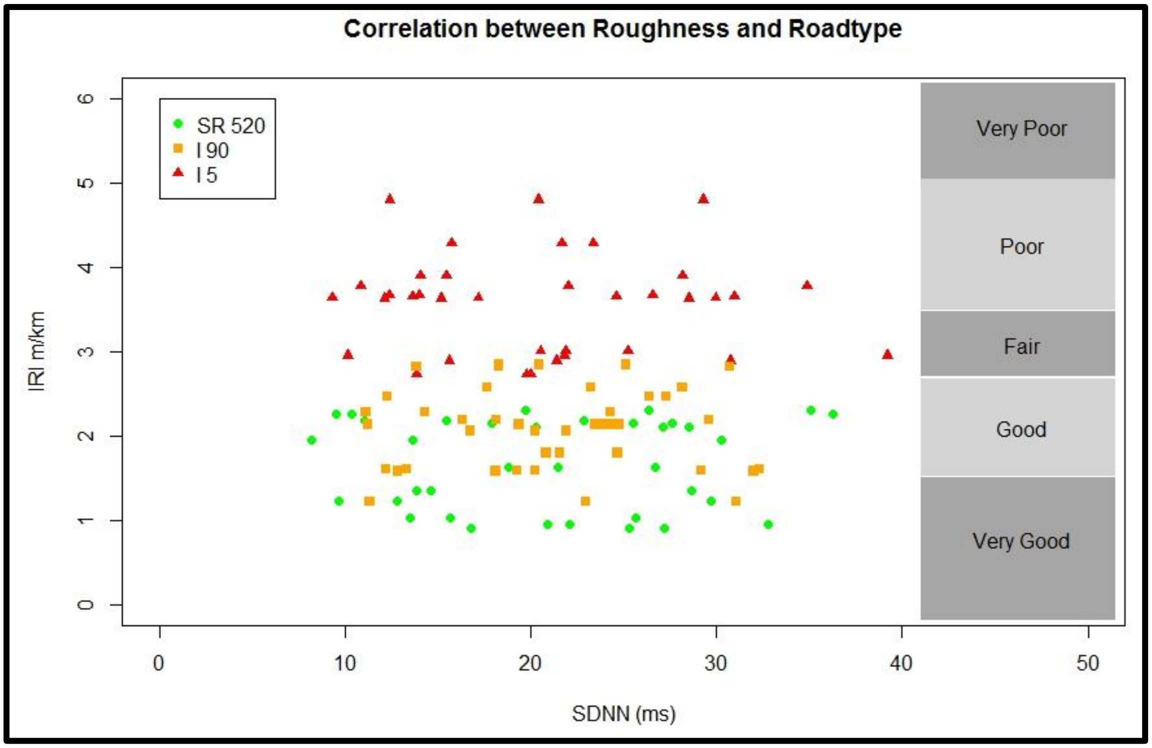

Figure 27: Correlation between road roughness (IRI) and road type

Future applications of this should sample longer segments of known continuous IRI values and with more fluctuations in IRI. Alternatively, data from the vehicles accelerometer could be substituted for indexing the roughness of the road.

CHAPTER 5: CONCLUSIONS

6.1 Discussion

The goal of this study was to determine how roadway surface conditions influenced driver behavior, using stress as an indicator of behavioral breakdown. This is ultimately important in understanding the value of pavement maintenance projects. This premise was examined using an instrumented vehicle in an on-road study. All participants completed the same drive, whether it was clockwise or counterclockwise. Since the route segments were symmetrical for inverse trips, each segment was driven at comparable speeds between subjects, and the drive was short enough to minimize HRV dependence on distance, participant data sets could be compiled.

Interesting findings include recorded cognitive workload to be elevated along the newer freeway pavement segment (I-90) and decreased along the segment under construction (SR-520). As hypothesized, drivers experienced increased stress along the rougher, older pavements (I-5) and low stress along the rural roads. However in contrast to the hypothesis, individual stress events along the rural roads were not adequately captured. All findings were consistently noticeable among all age groups and genders. Although the base levels of observed physiological responses were different across age and gender, the overall patterns of incremental change in response to cognitive demand was consistent across all groups; that is what is noteworthy (Mehler, et al., 2010).

The recorded stress along I-5 coincides with the documented IRI values which express unacceptable roughness. Historical data also indicated that this facility had the oldest segments of pavement. Also compared to the other roads, I-5 had the highest AADT and substantial truck volumes.

The low values for IRI along I-90 suggest stress induced from other variables were observed. I-90 is unique from the other facilities for its long tunnel sections and from this it can be inferred that the measured stress is reflective of a common notion called tunnel phobia. Several studies have investigated the influence of roadway tunnels on driver behavior and have found adverse responses from drivers in tunnel environments (Forbes, et al., 1958; Edie & Foote, 1958). In 1992 the Norwegian Public Roads Administration conducted a series of studies on driver perceptions and reactions to tunnel driving. These studies observed that 50% of drivers traveled above the speed limit in the middle of the tunnel, but below limit in the entrance and exit zones. Furthermore, these variations in speed were greater in tunnels than on the connecting roads. All drivers in these studies were also aware of the sudden changes in visibility when entering and leaving tunnels (Kvaale & Lotsberg, 2001). This stress credited to low illumination and constricting surroundings, known as tunnel phobia, was detected by the ECG data.

On the whole, most measurements for SR-520 indicated relatively low driver stress along the facility. By observation, most of the pavement was in good condition, with the exception of the construction section on the east approach, where heavy vehicles had torn up and rutted the pavement. A closer examination of continuous heart activity along the stretch, rather than discrete HRV parameters could expose significant differences between these rough and smooth segments. Instead it appears acute stress events were lost in using intervals and mean values. Future analysis should compile continuous heart rate (bpm) data and ECG tachograms (individual RR-interval variations). Instead, the heart rate variability analysis used captured low levels of stress, likely induced from the serene, environmental setting of the road.

Although AADT and IRI values were not readily available for the rural roads; it is a reasonable assumption to classify the roads as low volume and smooth. Recorded participant stress levels coincide with this assumption, in that cognitive demand was low along this section. By introducing another level of classifying safety critical events, future analysis could evaluate whether too low of cognitive workload was observed along these roads.

One heart activity analysis parameter alone is not enough to draw concrete conclusions from, but as shown in this study several parameters in conjunction with each other can validate trends and isolate outliers. This study found SDNN values the most consistent, which is a conclusion commonly found; Kuss et al (2008) reported highest precision in SDNN values as compared to other parameters.

The primary focus of this study was to use physiological measurements to detect trends in drivers across various roadway surface conditions. All age groups and genders had comparable responses, however the older group was noticeably most effected and the middle group least effected. The HRV parameters indicate that drivers became most adversely effected along rough pavement, routes of heavy traffic flow, and within roadway tunnel sections. However, the open road of the rural setting and SR-520 appeared correlated to lower stress.

Ultimately these findings can assist in enhancing transportation safety by understanding which conditions lead to the most vulnerable conditions for users. By reducing potential sources for induced workload, the frequency and severity of traffic crashes can also decrease (Kantowitz, Simsek; 2001). With this understanding of influences of roadway surface conditions and driver stress, transportation funding can be better prioritized.

6.2 Future Research

This study showed that physiological measurements do vary across roadway surface conditions and this should be explored further. Measures of stress can be captured with physiological, vehicle kinematics, and even survey data; each providing different insights on driver's ability to handle stress in safety critical situation.

With respect to physiological measures, future analysis could include more temporal analysis of the continuous heart activity that has been collected, as well as correlate across longer stretches of the same roadway conditions (e.g., 10 miles rather than 5 miles of Interstate 5). Longer stretches of roadway can provide more data to correlate the variations in IRI with the fluctuations in heart rate. Moreover, there can be differences between physiological measures collected from ECG when compared to EEG, and it would be interesting to understand whether the greater level of detail may provide better insights on driver stress. Also, developing a different means for classifying road roughness (e.g. using accelerometer output to quantify changes in vehicle position in x, y, and z position) could identify stronger correlations. The current study used GPS coordinates to quantify the latitude and longitude of the driver, but roughness is also based on elevation and this may have provided more insights on the smoothness of the drive.

Future data analysis can also look at more homogeneous groups using cluster analytic techniques. This could more specifically identify attributes that cause some drivers to be more susceptible to cognitive overload. Further, there were quite a few physiological measures examined independently in this study. However, there is most likely a great deal of correlation among these dependent variables and a factor analysis could provide some insights on latent variables that can capture constructs of several measures in the time and frequency domain.

Expanding upon the self-reporting analysis could also be valuable to better understand the factors influencing stress. For example, querying driver's in-route about their perceived stress or survey how familiar they were with each roadway facility after the drive.

Measures of stress examined in this study were compared to variations in road roughness. However, driver stress is based on many different road, vehicle, and environmental factors. And the methodology proposed in this study could be considered for examining driver workload while engaged in in-vehicle systems, reading dynamic message signs, and interpretation of complex intersection designs.

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REFERENCES

Acharya, U., Joseph, K., Kannathal, N., Lim, C., & Suri, J. (2006). Heart rate variability: a review. *Medical and Biological Engineering and Computing*, 44(12), 1031-1051.

Akselrod, S. (1995). Components of heart rate variability: basic studies. In M. Malik, & A. Camm (Eds.). *Heart Rate Variability* (pp. 147-164). Armonk, NY: Futura.

Allen, R. W., & Stein, A. C. (1987). The driving task, driver performance models and measurement. In *Proceedings of the 2nd International Symposium on Medicinal Drugs and Driving Performance.* Maastricht, Netherlands.

American Association of State Highway and Transportation Officials (AASHTO). (2009). *Rough Roads Ahead*. Available online: <http://roughroads.transportation.org/RoughRoads_FullReport.pdf>.

Apparies, R., Riniolo, T., & Porges, S. (1998). A psychophysiological investigation of the effects of driving longer-combination vehicles. *Ergonomics*, 41(5), 581–592.

Appel, M. L., Berger, R. D., Saul, J. P., Smith, J. M., & Cohen, R. J. (1989). Beat to beat variability in cardiovascular variables: noise or music? *Journal of the American College of Cardiology,* 14(5), 1139-1148.

Ascone, D., Lindsey, T., & Varghese, C. (2009). An examination of driver distraction. *National Center for Statistics and Analysis*, Report No. HS-811 216.

Baddeley, A. (1972). Selective attention and performance in dangerous environments. *British Journal of Psychology*, 63(4), 537-546.

Bao, S., & Boyle, L. N. (2008). Driver performance at two-way stop-controlled intersections on divided highways. *Transportation Research Record: Journal of the Transportation Research Board,* 2069, 26-32.

Bao, S., Boyle, L. N. (2009a). Age-related differences in visual scanning at median-divided highway intersections in rural areas. *Accident Analysis and Prevention*, 41(1), 146-152.

Bao, S., Boyle, L. N. (2009b). Driver safety programs: the influence on the road performance of older drivers. *Transportation Research Record: Journal of the Transportation Research Board*, 2096, 76-80.

Berntson, G., Bigger J., Eckberg, D., Grossman, P., Kaufmann, P., Malik, M., Nagaraja, H., Porges, S., Saul, J., Stone, P., & VanDerMolen, M. (1997). Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiol*, 34, 623–648.

Bharadwaj, A., & Kamath, U. (2011). Techniques for accurate ECG signal processing. *EE Times.* Available online: < http://www.eetimes.com/design/medical-design/4213140/Techniques-for-accurate-ECG-signal-processing>.

Bilchick, K., & Berger, R. (2006). Heart rate variability. *Journal of Cardiovascular Electrophysiology*, 17(6), 691–694.

Biocom Technologies (2009). *Heart Rate Variability Analysis Methodology*. Available online: <http://www.biocomtech.com/hrv-science/heart-rate-variability-methods>.

Boyce, T. E., & Geller, E. S. (2002). An instrumented vehicle assessment of problem behavior and driving style: do younger males really take more risks? *Accident Analysis & Prevention*, 34(1), 51-64.

Boyle, L. N., & Mannering, F. (2004). Impact of traveler advisory systems on driving speed: some new evidence. *Transportation Research Part C*, 12(1), 57-72.

Brookhuis, K. A., & De Waard, D. (2001). Assessment of drivers' workload: performance and subjective and physiological indexes. In P.A. Hancock, & P.A. Desmond (Eds.), *Stress, Workload, and Fatigue* (pp. 321-333). Mahwah, NJ: Lawrence Erlbaum Associates.

Cerutti, S., Bianchi, A. M., & Mainardi, L. T. (1995). Spectral analysis of the heart rate variability signal. In M. Malik, & A. Camm (Eds.). *Heart Rate Variability* (pp. 63-74). Armonk, NY: Futura.

Chliaoutakis, J. E., Demakakos, P., Tzamalouka, G., Bakou, V., Koumaki, M., & Darviri, C. (2002). Aggressive behavior while driving as predictor of self-reported car crashes. *Journal of Safety Research*, 33(4), 431-443.

Coughlin, J. F., Reimer, B., & Mehler, B. (2011). Monitoring, managing, and motivating driver safety and well-being. *IEEE Pervasive Computing*, 10(3), 14-21.

Dingus, T. A., Hulse, M. C., Mollenhauer, M. M., Fleischman, R. N., Mcgehee, D. V., & Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(2), 177-199.

Edie, L. C., & Foote, R. S. (1958). Traffic flow in tunnels. In *Proceedings of the Highway Research Board*, 37, 334-344.

Egelund, N. (1982). Spectral analysis of heart rate variability as an indicator of driver fatigue. *Ergonomics*, 27(7), 663-672.

Elander, J., West, R., & French, D. (1993). Behavioral correlates of individual differences in road-traffic crash risk: an examination of methods and findings. *Psychological Bulletin*, 113(2), 279-294.

Eriksson, J., Girod, L., Hull, B., Newton, R., Madden, S., & Balakrishnan, H. (2008). The pothole patrol: using a mobile sensor network for road surface monitoring. In *Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services.*

Evans, L. (1991). *Traffic Safety and the Driver*. New York, NY: Van Nostrand Reinhold.

Forbes, T. W., Zagorski, H. J., Holshouser, E. L., & Deterline, W. A. (1958). Measurement of driver reactions to tunnel conditions. In *Proceedings of the Transportation Research Board*, 37, 345-357.

Glendon, A. I., Dorn, L., Davies, D. R., Matthews, G., & Taylor, R. G. (1996). Age and gender differences in perceived accident likelihood and driver competences. *Risk Analysis*, 16(6), 755-762.

Gulian, E., Debney, L. M., Glendon, A. I., Davies, D. R., & Matthews, G. (1989). Coping with driver stress. In F. McGuigan, W. E. Sime, & J. M. Wallace (Eds.), *Stress and Tension Control* (Volume 3 pp. 173-186). New York, NY: Plenum.

Hakamies-Blomqvist, L., & Wahlström, B. (1998). Why do older drivers give up driving? *Accident Analysis & Prevention*, 30(3), 305-312.

Harris, K. F., & Matthews, K. A. (2004). Interactions between autonomic nervous system activity and endothelial function: a model for the development of cardiovascular disease. *Psychosomatic Medicine*, 66(2), 153-164.

Hartley, L., Arnold, P., Smythe, G., & Hansen, J. (1994). Indicators of fatigue in truck drivers. *Applied Ergonomics*, 25(3), 143–156.

Healey, J., & Picard, R. (2005). Detecting stress during real-world driving tasks using physiological sensors. *IEEE Transactions on Intelligent Transportation Systems*, 6(2), 156-166.

Helmreich, R., Chidster, T., Foushee, H., Gregorich, S., & Wilhelm, J. (1990). How effective is cockpit resource management training issues in evaluating the impact of programs to enhance crew coordination. *Flight Safety Digest*, 9(5), 1-17.

Hennessy, D., & Wiesenthal, D. (1997). The relationship between traffic congestion, driver stress and direct versus indirect coping behaviours. *Ergonomics*, 40(3), 348-361.

Hennessy, D., & Wiesenthal, D. (1999). Traffic congestion, driver stress, and driver aggression. *Aggressive Behavior*, 25(6), 409-423.

Hill, J. D., & Boyle, L. N. (2006). Assessing the relative risk of severe injury in automotive crashes for older female occupants. *Accident Analysis & Prevention,* 38(1), 148-154.

Hill, J. D., & Boyle, L. N. (2007). Driver Stress as influenced by driving maneuvers and roadway conditions. *Transportation Research Part F*, 10(3), 177-186.

Hulse, M. C., Dingus, T. A., Fischer, T., & Wierwille, W. W. (1989). The influence of roadway parameters on driver perception of attentional demand. *Advances in Industrial Ergonomics and Safety,* 1, 451-456.

Ivancevich, J., Matteson, & Preston, C. (1982). Occupational stress, type A behavior, and physical well being. *Academy of Management Journal*, 25(2), 373-391.

Javadi, M., Arani, S., Sajedin, A., & Ebrahimpour, R. (2012). Classification of ECG arrhythmia by a modular neural network based on Mixture of Experts and Negatively Correlated Learning. *Biomedical Signal Processing and Control*, in press.

Jorna, P. G. A. M. (1993). Heart rate and workload variations in actual and simulated flight. *Ergonomics*, 36(9), 1043-1054.

Kantowitz, B. H., & Simsek, O. (2001). Secondary-task measures of driver workload. In P.A. Hancock, & P.A. Desmond (Eds.), *Stress, Workload, and Fatigue* (pp. 395-408). Mahwah, NJ: Lawrence Erlbaum Associates.

Kasap, Z., Moussa, B., Chaudhuri, P., & Magnenat-Thalmann, N. (2009). Making them remember - emotional virtual characters with memory. *IEEE Computer Graphics and Applications*, 29(2), 20-29.

Kleiger, R., Stein, P., & Bigger, J. (2005). Heart rate variability: measurement and clinical utility. *Annals of Noninvasive Electrocardiology*, 10(1), 88–101.

Kleiger, R., Stein, P., Bosner, M., & Rottman, J. (1992). Time-domain measurements of heart rate variability. In M. Malik, & A. Camm (Eds.). *Heart Rate Variability* (pp. 33-46). Armonk, NY: Futura.

Kobayashi, H., Park, B., & Miyazaki, Y. (2012). Normative references of heart rate variability and salivary alpha-amylase in a healthy young male population. *Journal of Physiological Anthropology*, 31, 1-9.

Kontogiannis, T. (2006). Patterns of driver stress and coping strategies in a Greek sample and their relationship to aberrant behaviors and traffic accidents. *Accident Analysis & Prevention*, 38(5), 913-924.

Kopin, I., Eisenhofer, G., & Goldstein, D. (1988). Sympathoadrenal medullary system and stress. *Advances in Experimental Medicine and Biology*, 245, 11-23.

Kuemmel, D., Jaeckel, J., Satanovsky, A., Shober, S., & Dobersek, M. (1996). Noise characteristics of pavement surface texture in Wisconsin. *Transportation Research Board*, Report No. 1544, 24-35.

Kuss, O., Schumann, B., Kluttig, A., Greiser, K. H., & Haerting, J. (2008). Time domain parameters can be estimated with less statistical error than frequency domain parameters in the analysis of heart rate variability. *Electrocadiology,* 41(4), 287-291.

Kvaale, J., & Lotsberg, G. (2001). Measures against monotony and phobia in the 24.5 km long laerdal tunnel in Norway. *Proceedings from the 4th Symposium on Strait Crossings*, 469-476.

Landstrom, U., Englund, K., Nordstrom, B., & Astrom, A. (1998). Laboratory studies of a sound system that maintains wakefulness. *Perceptual and Motor Skills*, 86(1), 147-161.

Lazarus, R. S., & Folkman, S. (1984). *Stress, Appraisal, and Coping* (pp. 19). New York, NY: Springer Publishing Company.

Lee, H., Kim, J., Kim, Y., Baek, J., Ryu, M., & Park, K. (2007a). The relationship between HRV parameters and stressful driving situation in the real road. In *Proceedings of the 6th International Special Topic Conference on Information Technology Applications in Biomedicine*, 198-200.

Lee, H., Choi, J., Kim, J., Kim, Y., Baek, H., Ryu, M., Soh, R., & Park, K. (2007b). Nonintrusive biosignal measurement system in a vehicle. In *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* 2303-2306.

Li, C., Zheng, C., & Ta, C., 1995. Detection of ECG characteristic points using wavelet transforms. *IEEE Transactions on Biomedical Engineering*, 42(1), 21–28.

Li, Z., Jiao, K., Chen, M., & Wang, C. (2004). Reducing the effects of driving fatigue with magnitopuncture stimulation. *Accident Analysis & Prevention*, 36(4), 501–505.

Liu, S., Lin, C., & Chao, W. (2004). The short-time fractal scaling of heart rate variability to estimate the mental stress of driver. In *Proceedings of the IEEE International Conference on Networking, Sensing and Control*, 2, 829–833.

Lourens, P. F., Vissers, J. A. M. M., & Jessurn, M. (1999). Annual mileage, driving violations, and accident involvement in relation to drivers' sex, age, and level of education. *Accident Analysis & Prevention*, 31(5), 593-597.

Lu, Q., Kohler, E., & Harvey, J. (2010). Field investigation of acoustic performance of various asphalt surface mixes. In *Proceedings of the 10th International Conference of Chinese Transportation Professionals*, 3937-3947.

Malliani, A., Pagani, M., Lombardi, F., & Cerutti, S. (1991). Cardiovascular neural regulation explored in the frequency domain. *Circulation*, 84, 482-492.

Matthews, G. (2001). Levels of transaction: a cognitive science framework for operator stress. In P.A. Hancock, & P.A. Desmond (Eds.), *Stress, Workload, and Fatigue* (pp. 5-33). Mahwah, NJ: Lawrence Erlbaum Associates.

Matthews, G., & Desmond, P. A. (1995). Stress as a factor in the design of in-car driving enhancement systems. *Le Travail Humain: A Bilingual and Multi-Disciplinary Journal in Human Factors*, 58(2), 109-129.

Matthews, G., & Desmond, P. A. (2001). Stress and driving performance: implications for design and training. In P.A. Hancock, & P.A. Desmond (Eds.), *Stress, Workload, and Fatigue* (pp. 211-231). Mahwah, NJ: Lawrence Erlbaum Associates.

Matthews, G., Dorn, L., Hoyes, T. W., Davies, R. D., Glendon, A. I., & Taylor, R. G. (1998). Driver stress and performance on a driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 40(1), 136-149.

Matthews, G., Joyner, L., & Newman, R. (1999a). Age and gender differences in stress responses during simulated driving. In *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, 1007-1011.

Matthews, G., Tsuda, A., Xin, G., Ozeki, Matthews, G., Tsuda, A., Xin, G., & Ozeki., Y. (1999b). Individual differences in driver stress vulnerability in a Japanese sample. *Ergonomics*, 42(3), 401-415.

McKenzie, B., & Rapino, M. (2011). Commuting in the United States: 2009. *United Statues Census Bureau*. Available online: <http://www.census.gov/prod/2011pubs/acs-15.pdf>.

Mehler, B., Reimer, B., & Coughlin, J. (2010). Physiological reactivity to graded levels of cognitive workload across three Age groups: an on-road evaluation. In *Proceedings of the Human Factors and Ergonomics Society 54th Annual Meeting*, 2062-2066.

Messer, C. J., Mounce, J. M., Brackett, R. Q. (1979). Highway geometric design consistency related to driver expectancy, Volume III – Methodology for evaluating geometric design consistency. *Federal Highway Administration*, Report No. FHWA/RD-81/037.

Miyaji, M., Kawanaka, H., & Oguri, K. (2010). Effect of pattern recognition features on detection for driver's cognitive distraction. In *Proceedings of the IEEE 13th International Conference on Intelligent Transportation Systems*, 605-610.

Montano, N., Ruscone, T.G., Porta, A., Lombardi, F., Pagani, M., & Malliani, A. (1994). Power spectrum analysis of heart rate variability to assess the changes in sympathovagal balance during graded orthostatic tilt. *Circulation*, 90(4), 1826-1831.

Moray, N. (1979). *Mental Workload: Its theory and measurement.* New York, NY: Plenum.

Mulder, G. (1986). The concept and measurement of mental effort. In G. R. J. Hockey, A. W. K. Gaillard, & M. G. H Coles (Eds), *Energetics and humans information processing* (pp. 175-198). Dordrecht, Netherlands: Martinus Nijhoff.

Mulder, L. J. M. (1992). Measurement and analysis methods of heart rate and respiration for use in applied environments. *Biological Psychology*, 34, 205-236.

Ng, L., Barfield, W., & Mannering, F. (1995). A survey-based methodology to determine information requirements for advanced traveler information systems. *Transportation Research Part C*, 3(2), 113-127.

Niskanen, J., Tarvainen, M., Ranta-Aho, P., & Karjalainen, P. (2004). Software for advanced HRV analysis. *Computer Methods and Programs in Biomedicine*, 76(1), 73-81.

Norris, F., Matthews, A., & Riad, J. (2000). Characterological, situational, and behavioral risk factors for motor vehicle accidents: a prospective examination. *Accident Analysis & Prevention,* 32(4), 505-515.

Noy, Y. I. (1989). Intelligent route guidance: will the new horse be as good as the old? In *Proceedings of the IEEE Vehicle Navigation and Information Systems Conference,* 49-55.

Neuman, T. R. (1992). Roadway geometric design. In J.L Pline (Ed.), *Traffic engineering handbook Institute of Transportation Engineers* (4th ed., pp. 154-203). Englewood Cliffs, NJ: Prentice-Hall.

O'Hanlon, J. (1972). Heart rate variability: a new index of driver alertness/fatigue. *Society of Automotive Engineers,* Report No. 720141.

Ohsuga, M., Shimono, F., & Genno, H. (2001). Assessment of phasic work stress using autonomic indices. *Journal of Psychophysiology*, 40(3), 211-220.

Pagani, M., Lucini, D., Rimoldi, O., Furlan, R., Piazza, S., & Biancardi, L. (1995). Effects of physical and mental exercise on heart rate variability. In M. Malik, & A. Camm (Eds.). *Heart Rate Variability* (pp. 245-266).

Parasuraman, R., & Riley, V. (1997). Humans and automation: use, misuse, disuse, abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(2), 230-253.

Partin, D., Sultan, M., Thrush, C., Prieto, R., & Wagner, S. (2006). Monitoring driver physiological parameters for improved safety. *Society of Automotive Engineers*, Report No. 01-1322.

Pavement Interactive. (2012). Available online: < http://www.pavementinteractive.org>.

Ranney, T., Mazzae, E., Garrott, R., & Goodman, M. (2000). NHTSA driver distraction research: past, present and future. In *Internet Forum on Driver Distraction*, National Highway Traffic Safety Administration.

Regan, M., Lee, J., & Young, K. (2009). *Driver Distraction: Theory, Effects, and Mitigation*. Boca Raton, FL: CRC Press.

Reimer, B., & Mehler, B. (2011). The impact of cognitive workload on physiological arousal in young adult drivers: a field study and simulation validation. *Ergonomics*, 54(10), 932-942.

Roediger, H., & McDermott, K. (2000). Tricks of memory. *Current Directions in Psychological Science*, 9(4), 123-127.

Ryan, G. A., Legge, M., & Rosman, D. (1998). Age related changes in drivers' crash risk and crash type. *Accident Analysis & Prevention*, 30(3), 379-387.

Sayers, M., Gillespie, T., & Queiroz, C. (1986). The international road roughness experiment: a basis for establishing a standard scale for road roughness measurements. *Transportation Research Board*, Report No. 1084, 76-85.

Selzer, M., & Vinokur, A. (1975). Role of life events in accident causation. *Mental Health and Society*, 2, 36-54.

Shafizadeh, K., & Mannering, F. (2003). Acceptability of pavement roughness on urban highways by driving public. *Transportation Research Record* 1860, 187-193.

Shankar, V., & Mannering, F. (1998). Modeling the endogeneity of lane-mean speeds and lane-speed deviations: a structural equations approach. *Transportation Research Part A*, 32(5), 311-322.

Simon, F., & Corbett, C. (1996). Road traffic offending, stress, age, and accident history among male and female drivers. *Ergonomics*, 39(5), 757-780.

Simonson, E., Baker, C., Burns, N., Keiper, C., Schmitt, O. H., & Stackhouse, S. (1968). Cardiovascular stress (electrocardiographic changes) produced by driving an automobile. *American Heart Journal*, 75(1), 125-135.

Sloan, R. P., Shapiro, P. A., Bagiella, E., Boni, S. M., Paik, M., Bigger, J. T., Steinman, R. C., & Gorman, J. M. (1994). Effect of mental stress throughout the day on cardiac autonomic control. *Biological Psychology*, 37(2), 89-99.

Smart, R., Stoduto, G., Mann, R., & Edward, M. (2004). Road rage experience and behavior: Vehicle, exposure, and driver factors. *Traffic Injury Prevention*, 5(2004), 343-348.

Snyder, M., & White, P. (1982). Moods and memories: elation, depression, and the remembering of the events of one's life. *Journal of Personality*, 50(2), 149-167.

Steptoe, A., & Sawada, Y. (1989). Assessment of baroreceptor reflex function during mental stress and relaxation. *Psychophysiology*, 26(2), 140.

Stokols, D., Novaco, R. W., Stokols, J., & Campbell, J. (1978). Traffic congestion, Type A behaviour, and stress. *Journal of Applied Psychology*, 63, 467-480.

Tattersall, A., & Hockey, G. (1995). Level of operator control and changes in heart rate variability during simulated flight maintenance. *Human Factors*, 37(4), 682-698.

Tarkiainen, T., Timonen, K., Tiittanen, P., Hartikainen, J., Pekkanen, J., Hoek, G., Ibald-Mulli, A., & Vanninen, E. (2005). Stability over time of short-term heart rate variability. *Clinical Autonomic Research*, 15(6), 394-399.

Turner, C. W., Layton, J. F., & Simons, L.S. (1975). Naturalistic studies of aggressive behaviour: aggressive stimuli, victim visibility and horn honking. *Journal of Personality and Social Psychology*, 31, 1098-1107.

Verwey, W. B. (1991). Towards guidelines for in-car information management: driver workload in specific driving situations. *TNO Institute for Perception*, Report No. IZF 1991 C-13, Soesterberg, Netherlands.

Veryway, W. B., Veltman, H. A. (1996). Detecting short periods of elevated workload: a comparison of nine workload assessment techniques. *Journal of Experimental Psychology: Applied*, 2(3), 270-285.

Vidulich, M., Stratton, M., & Wilson, G. (1994). Performance-based and physiological measures of situational awareness. *Aviation, Space and Environmental Medicine*, 65, 7-12.

Westerman, S. J., & Haigney, D. (2000). Individual differences in driver stress, error, and violation. *Personality and Individual Differences*, 29(5), 981-998.

Wickens, C., Gordon, S., & Liu, Y. (1998). *An Introduction to Human Factors Engineering*. New York, NY: Longman Publishing.

WSDOT. (2004). *State Materials Laboratory*. Available online: <http://wspms.ce.washington.edu/>.

WSDOT. (2010). *Pavement Roughness (IRI) Report: 2010*. Available online: <http://www.wsdot.wa.gov/Business/MaterialsLab/Pavements/PavementNotebook.htm>.

WSDOT. (2011a). *2011 Annual Traffic Report*. Available online: <http://www.wsdot.wa.gov/mapsdata/travel/pdf/Annual_Traffic_Report_2011.pdf>.

WSDOT. (2011b). *Quieter Pavement Performance in Washington*. Available online: <http://www.wsdot.wa.gov/NR/rdonlyres/0B899766-DB13-4AAD-9439-D3CE132769CB/0/QuieterPavement060711.pdf>.

Yagil, D. (1998). Gender and age-related differences in attitudes toward traffic laws and traffic violations. *Transportation Research Part F*, 1(2), 123-135.

Yan, X., Radwan, E., & Guo, D. (2007). Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis & Prevention*, 39(4), 843-852.

Zhao, X., Fang, R., Xu, S., Rong, J., & Liu, X. (2010). Sound as a countermeasure against driving fatigue based on ECG. In *Proceedings of the 10th International Conference of Chinese Transportation Professionals*, 401-413.

Zhao, C, Zhao, M., Liu, J., & Zheng, C. (2012). Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. *Accident Analysis and Prevention*, 45, 83-90.