An Approximation of Studded Tire Vehicle Volumes Utilizing Sound Data

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Abstract

The purpose of this study was to determine if sound could be used as a defining parameter to distinguish vehicles using studded tires from all other vehicle types. Vehicle sound data were collected using a sound meter device during the winter and summer seasons along a two-lane rural highway (State Highway 8) and a divided multi-lane highway (US-95) near Moscow, Idaho. The study examined variables including vehicle type, season, travel lane, and highway type. Based on the results, the study concluded that while vehicles with studded tires generated a higher decibel range that most passenger vehicles without studded tires, the range could not be differentiated from many pick-up trucks and semi-trucks with louder engine noises. While the results suggest that data collection methods using sound would require a secondary source such as video or a field observer in order to definitively identify vehicles with studded tires, an approximation method based on estimating the number of vehicles and the percentage of vehicles with studded tires produced results that were comparable to previously established methods.

Acknowledgements

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Dedication

I dedicate this work to my mother, father, sister, brother, my entire family, and all my friends as they have supported me unconditionally along this journey. Without their motivation and encouragement, this research would have not been possible. I would also like to dedicate this work to my beloved country Libya and hope that I can contribute back with the knowledge I have accumulated through my academic journey.

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Chapter 1: Introduction

Studded tires are used by drivers during winter months to increase vehicle traction and performance. While the use of studded tires provides these drivers with an added level of reassurance, the interaction between the studded tire and the roadway contributes to the pavement rutting and the potential for hydroplaning. The process of quantifying when a roadway surface needs to be repaired can be enhanced if studded tire vehicle volumes, and other contributors such as heavy vehicle volumes, are carefully measured. To date, studded tire usage has typically been determined from parking lot and phone surveys.

The main objective of this research was to determine if sound could be used as a parameter to determine studded tire vehicle volumes along a highway. Sound data for different time durations were collected on two separate highways in the surrounding area of Moscow, Idaho for analysis purposes. This data were collected in shorter and longer durations. The shorter segment was accompanied by a video recording to compare with actual traffic volumes, and the longer segment was used to apply a prediction method after analyzing the shorter one. The video footage was used to analyze vehicle types and identify decibel ranges, especially for vehicles with studded tires. By general observation, the presence of metal studs within the tires increased sound compared to non-studded tires. To further investigate the sound data collected, an ANOVA analysis was conducted to explore how different variables affected the data as a whole. In addition, a model was created to predict the probability of a vehicle being either a passenger vehicle, truck, passenger vehicle with studs, or other vehicle types.

In Chapter 2, a literature review describes previous sound related research and topics of interest. Chapter 3 describes the method for data collection and a newly introduced method for counting vehicle volumes and studded tire vehicle volumes using sound data. Chapter 4 describes the results from the data collection, highlighting studded tire vehicle results in comparison with other vehicle types. The study results include a statistical analysis conducted in R exploring different variables that influenced the data collection process along with a probability prediction model for the sound data. The conclusions in Chapter 5 highlight the key findings and identify areas for future study.

Chapter 2: Literature Review

A literature review was conducted to examine previous studies that focused on sound generated by studded tire and pavement interaction and the physical impacts of this interaction. This chapter will describe the rutting damage caused by studded tires, discuss studded tire data collection methods, highlight the sound effects produced by studded tires, and summarize state-level legislation, specifically for Idaho and Washington, as it relates to studded tires.

Rutting damage

Studded tires contribute to pavement rutting damage during the winter months wherever snow and ice are common. Pavement materials such as hot mix asphalt and Portland cement concrete tend to contract with low temperatures. The binding materials within these pavement surfaces also weaken with low temperatures which decreases ductility (Kumardas, 2013). The process of freezing and thawing results in surface cracks which weakens the pavement. When studded tires are introduced during winter months, the metal studs from the tires cause a higher impact force on the road surface which contributes to greater cracking damage. In a previous study, the rutting damage caused by passenger vehicles with studded tires was compared with heavy truck wheel axial loads; the wear rates were 0.0116 inches per 100,000 studded vehicles compared with average rut rates due to heavy wheel loads of 0.0049 inches per 100,000 trucks (Abaza, 2019). Rutting damage caused by vehicles with studded tires can be remedied in a timely manner if both the location and volume of these vehicles are known. This knowledge could allow for mitigation such as strengthening the pavement surface by increasing thickness or introducing additional binding materials.

Pavement wearing due to studded tires

Angerinos (1999) explored the characteristics of studded tires that highly contributed to pavement wear. Some of the characteristics were stud protrusion, stud weight, driving speed, number of studs per tire, and stopping effectiveness. Wear rates were higher for asphalt concrete pavement surfaces versus Portland cement concrete per one million passes of studded tires. Wear rates were 0.4 inches per million studded tire passes for California AC, and less than 0.1 inches for Oregon PCC. Stud protrusion was one of the characteristics that directly impacted pavement wear, and mainly depended on the structure of the stud.

The structure of wheel studs has evolved over time to reduce the overall protrusion effect on pavement. Research work performed in Finland concluded that pavement wear in cubic centimeters increased with the increase of stud weights (Unhola, 1997). Stud weights start at 1.0 grams which resulted in 0.25 cm^3 wear and increased up to 0.80 cm^3 wear at a stud weight of 3.0 grams.

(Brunnette, (1995) examined vehicle speeds and their relationship with pavement wear and concluded that an increase in speed caused an increase in stud dynamic force which affected the pavement, resulting in higher wear rates. Table 2.1 shows the results from Unhola's study. As an example, vehicle speeds at 50 miles per hour contributed 0.02 in^3 of pavement wear per million studded tire passes.

Table 2.1: Pavement wear due to vehicle speed

Vehicle Speed (mph)	Pavement Wear (in^3)
30	0.012
37	0.014
43	0.016
50	0.020
55	0.026
62	0.034
67	0.048
74	0.073

Related data collection methods

Previous collection methods for studded tire volumes have been based on phone surveys and parking lot surveys. The purpose of a phone survey is to get an approximation of the number of vehicles with studded tires based on the verbal responses provided by the recipient of the call. An initial set of questions is formed, and responses are then collected over the phone. For example, a study conducted by Portland State University in partnership with the Oregon Department of Transportation (ODOT) used the phone survey collection method to conclude that the use of studded tires in Oregon declined over time (Shippen, 2014). Responses were divided based on the five regions identified by ODOT, and the study concluded that 16% of registered vehicles were equipped with studded tires in 1995, but that value dropped to 7.9% nearly two decades later (Shippen, et al., 2014).

By comparison, parking lot surveys are based on field work where a data collector analyzes and counts vehicles by sight. The chosen sites are typically larger commercial store parking lots or shopping malls in which several hundred vehicles are simultaneously present. Based on an analysis by Malik (2000), phone surveys were more efficient than parking lot surveys as phone surveys were able to collect more winter driving data such as number of studded tires on vehicles and other information such as when users prefer installing studded tires. The phone survey results gave use patterns and percentages of studded tires, and they also deduced usage growth rates by Oregon residents.

One of the interesting results from a phone survey was that cars with studded tires typically have studs installed on all four wheels while earlier studies had indicated a mixture of installation preferences (Shippen, et al., 2014).

Defining sound

Sound is transmitted through waves and these waves can travel through air, water, and other surfaces. A sound wave has five main properties including wavelength, time period, amplitude, frequency, and speed. Human beings process these waves based on their frequency and frequency refers to the way in which sound waves oscillate while travelling to our ears, meaning that they alternate between compressing and stretching the medium, which in most cases is air (Attune, 2021). Sound waves travel at the same speed in the same medium. Sound is typically measured in decibel units which is referred to as sound pressure that has a Pascal (Pa) unit. Sound frequency refers to the number of waves produced in one second and is measured in Hertz. If ten complete waves are produced in one second, then the frequency of the waves will be ten Hertz (Hz) or ten cycles per second. Low frequency sounds are typically measured at 500 Hz or below, and examples include earthquakes, elephant roars, and noise caused by severe weather. High frequency sounds are comparably measured at about 2000 Hz or higher, and examples are whistles, sounds caused by mosquitos, and fingernails on a chalkboard.

Hertz and decibels are both sound units, though one measures frequency and the other measures intensity. Frequency represents the number of occurrences per unit of time, while the decibel unit is used to measure the intensity of a sound wave (differencebetween, 2011). A high frequency does not necessarily mean a louder noise, but louder noises tend to have higher intensities and equate to higher decibels (Encyclopedia Britannica, 2021). The decibel unit expresses the relationship between two physical quantities which are sound pressure level and sound pressure. To reach a point where sound recordings will be convenient to receive, understanding the frequency levels at which these recordings are taken is important.

Sound effects from studded tire vehicles

The sound resulting from studded tires are based on the interaction with the pavement surface, and processing and converting that sound into something audible will be convenient for volume data collection. Johnsson (2013) aimed to achieve this objective by exploring the effects of stud patterns and wheel types because some studded tire wheels have more or less studs than others which can affect the sounds produced. Also, the number and placement of tire studs depend on the tread pattern of the tire itself. To simulate the sound of a stud hitting the surface of a pavement, Johnsson (2013) used an impact hammer with a steel tip. Multiple tests with different tires were conducted, and the recordings used a free field microphone positioned 0.5 meters from the center of the rim. The study concluded that there was a significant difference on sound pressure based on the stud tire response and the stud pattern inside the car compartment. The speed also had a significant effect on the perceived annoyance from the different studded tire patterns and responses (Johnsson, 2013)

Johnsson and Nykanen (2010) previously explored the effects of stud patterns and wheel types because some studded tire wheels have more studs than others which can affect the sounds produced. A similar study recorded studded tire sound using acoustic emission and piezoelectric sensors (Schumacher, (2010). An experiment was performed on a bridge with acoustic sensors placed beneath it. Studded tires on passenger vehicles were found to produce a unique response on the acoustic emission sensing system resulting in a higher amplitude recording versus trucks (Schumacher, 2010). The study concluded that studded tire stress waves can be differentiated from trucks and passenger vehicles with studded tires over a passing bridge. Studded tires were found to produce a unique recording on the acoustic emission sensing system which was higher at a higher amplitude versus trucks and passenger vehicles without studs. Rebar strain detectors were also placed under thebridge to detect load magnitude, and studded tires had smaller rebar strain values compared to trucks and passenger vehicles without studs.

A study from Sweden examined the noise aspect caused by studded tires on pavement surfaces. Noise measurements were carried out by the close proximity method where a measurement trailer was used with microphones close to the tires (Vieira, 2018). The results indicated that studded tires are roughly 6 to 10 decibel (dB) units louder than regular tires. A separate study determined that at speeds between approximately 40 and 55 miles per hour (mph) the effect of the studs produces a noise increase of approximately 2 to 6 (dBs) in the frequency range of 500-5000 Hz and 5-15 dB above 5000 Hz (Kongrattanaprasert, (2010).

It has been concluded that noises generated from vehicle tires dominate all other projected noises 90% of the time (Sandberg, 2002). Zhang (2014) examined the frequency level of vehicles with noises connected to road features and tried to separate other parameters such as engine noise from the important noises for a pavement study. When driving, the driver will usually notice tire noise above all other noise, provided that the engine works efficiently. In order to record the targeted noise of studded tires, the road features affecting these generated sounds must be identified, so it is necessary to understand how pavement surface types and their properties affect data collection. A Northeastern University study on studded tires and all-season tires compared sound pressure and recorded frequency levels. Test vehicles were driven at 20 miles per hour (mph), 30 mph, and 40 mph and each run was 200 feet. The results from the study concluded that the increased sound emission from studded tires is concentrated at high frequencies above 6 kHz. Studded tires were higher in sound pressure versus all season tires at all test speeds (Zhang, 2014).

AASHTO standards for wayside sound measurements

The US Federal Highway Administration released a noise measurement handbook in June, 2018 that covers guidelines on how to plan a noise measurement program for different purposes such as measuring noise effects from highways on urban communities. The handbook provided guidance on which measurement methods should be used based on different projects, and measurement instrumentation (FHWA-HEP, 2018). The FHWA recommended microphones to be placed at 5 feet above the ground surface to be representative of ear height for a standing person.

The AASHTO handbook recommended taking video footage for traffic counts as it is easier to analyze later. Time synchronization between acoustic instruments and the video camera was recommended. AASHTO provided guidelines designed to capture noises relative to buildings off the highway and recommended placing microphones 25 feet from the fog line of the nearest lane, and then another microphone 10 feet away from the first microphone moving towards the building of interest. This was designed to capture noises that affected neighborhood residents.

This handbook also covered other factors that could affect the data collection process such as wind and temperature. It provided classes of wind conditions that would affect the results from the sound meters, and recommended not taking sound measurements when wind exceeded 11mph regardless of direction. Temperatures were recommended to be measured at two heights above ground to precisely find parameters that could affect the data collection process. (FHWA-HEP, 2018).

Idaho and Washington studded tire legislations

Studded tire legislation for the states of Idaho and Washington were reviewed for comparison purposes. Some similarities between the states were observed regarding permitted dates, tire structure restrictions, and highway restrictions. In the state of Idaho, where this study was carried out, studded tires are permitted for use from October 1st to April 30th each year. Studded tires are permitted for use in Washington from November 1st to March 31st, and these dates can be extended if there is a crisis that prevents people from having access to changing their tires. Also, the severity of winters and how much snow falls during the season can affect this legal period.

In terms of tire structure, Idaho statute Title 49 states that no vehicle tire on a highway "shall have on its periphery any block, stud, flange, cleat, spike, or any other protuberance of any material other than rubber which projects beyond the tread of the traction surface of the tire". However, under Title 49-948 (Motor Vehicles), Chapter 9 (Vehicle Equipment), the Idaho statute states that studded tires on vehicles can be used when required for safety because of snow or rough winter conditions. There is also a list of conditions that the Idaho legislature enforces on retailer shops that install studded tires. These conditions consist of the type and size of tire, and the weight of studs depending on tire size. The entire legislation for both Idaho and Washington is listed in the Appendix.

Chapter 3: Methods

For this study, two highway locations were chosen for data collection (see Figure 3.1). The locations were selected because they were representative examples of area highways, and the Idaho Transportation Department (ITD) collects vehicle volume data in the immediate vicinity. The first site was located between Moscow, ID and Troy, ID on ID-8. This facility was a two- lane highway with a posted speed limit of 60 miles per hour. The second site was located between Moscow, ID and Lewiston, ID on US-95. This divided highway has two lanes in each direction and the southbound direction was chosen for data collection purposes. The posted speed limit at this site was 65 miles per hour.

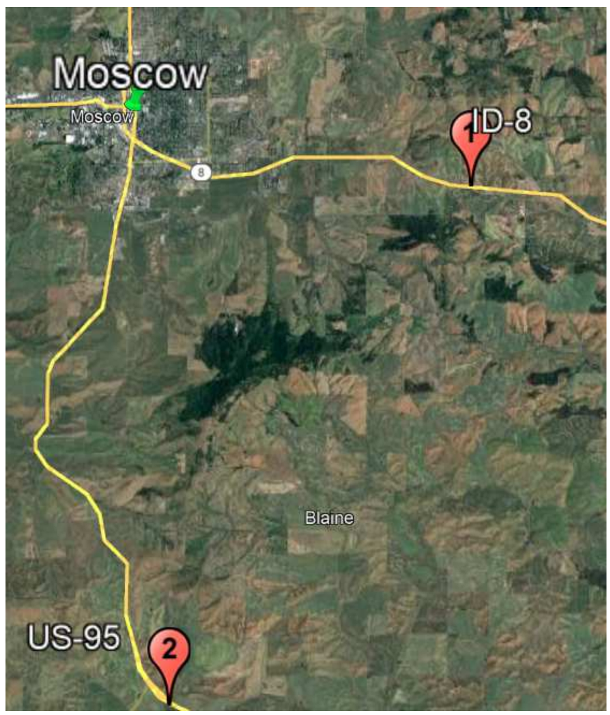

Figure 3.1: Site locations

For this study, several data sets were collected during both the winter and summer seasons:

- Two one-hour data sets with video footage on US-95 (collected on Thursday, December 10, 2020 and Thursday, June 17, 2021)
- Two one-hour data sets with video footage on ID-8 (collected on Thursday, March 4, 2021 and Wednesday, June 9, 2021)
- Two seven-hour data sets without video footage on US-95 (collected on Tuesday, January 12, 2021 and Thursday, June 17, 2021)

- Two seven-hour data sets without video footage on ID-8 (collected on Wednesday, January 20, 2021 and Wednesday, June 9, 2021)

Each one-hour data set was collected with video footage so that each passing vehicle could be identified and associated with the decibel readings from the sound meter. The video footage included a sound recording to identify the vehicles with studded tires. Manual vehicle counts were also collected in the field to provide additional assessment of studded tire vehicle volumes.

Field Setup

Since the AASHTO wayside sound measurement guidelines were primarily focused on measuring noise levels that affected nearby residential areas, the recommended microphone distances from those guidelines were referenced but not replicated. The goal of this research was to collect vehicle sound on the highway as closely and safely as possible. The sound meter devices were placed approximately five feet from the fog line of the highway (see Figure 3.2) with a camera placed adjacent to the sound meter. Microphones were placed on the stands the instruments came with which lifted the microphones not more than one foot off the ground which was sufficient to capture vehicle and tire sounds. The camera captured video quality in 1080p (Full HD) definition. For each one-hour data set, a manual count of the vehicle volumes was also conducted. There were at least two people present on site to assist with the counting process.

Figure 3.2: Field setup of sound meters (along US-95)

A sound level meter (PCE-322A professional Class II) with built-in data-logging functionality was used for this study. While there were many device options to choose from, the research team sought to use a device that was both economical and portable. This particular sound level meter provided a user-friendly interface, an ability to record data up to 30 hours, and the flexibility to transfer data. The sound level meter recorded a decibel reading each second and had a maximum storage capacity of 32,700 readings, which well exceeded the needs of this study.

Two sound level meters were used at each site. During initial testing, it was determined that relying on one sound meter to collect data was not always reliable. For this reason, two sound level meters were used in tandem and the average decibel reading from both sound level meters were then used for analysis purposes.

Data from the sound meters were then exported to Excel files for analysis. Pictures of the info display on the sound meters were taken to synchronize time between the sound equipment and video camera.

Figure 3.3: Sound meter display

Vehicle classifications

For this study, vehicles were classified into four categories including passenger vehicles, trucks, passenger vehicles with studded tires, and other vehicles such as semi-trucks. Passenger vehicles consisted of sedans, sport utility vehicles, coupes, hatchbacks, and compact vehicles. Pickup trucks represented all vehicles with an open cargo area. Other vehicles were comprised of recreational vehicles and semi-trucks. Finally, vehicles with studded tires represented all passenger vehicles with studded tires. Based on the FHWA classifications (see Figure 3.4), the most common vehicles seen in the field were categorized as Class 2, Class3, and Class 9 and 10 (Federal Highway Administration, 2013).

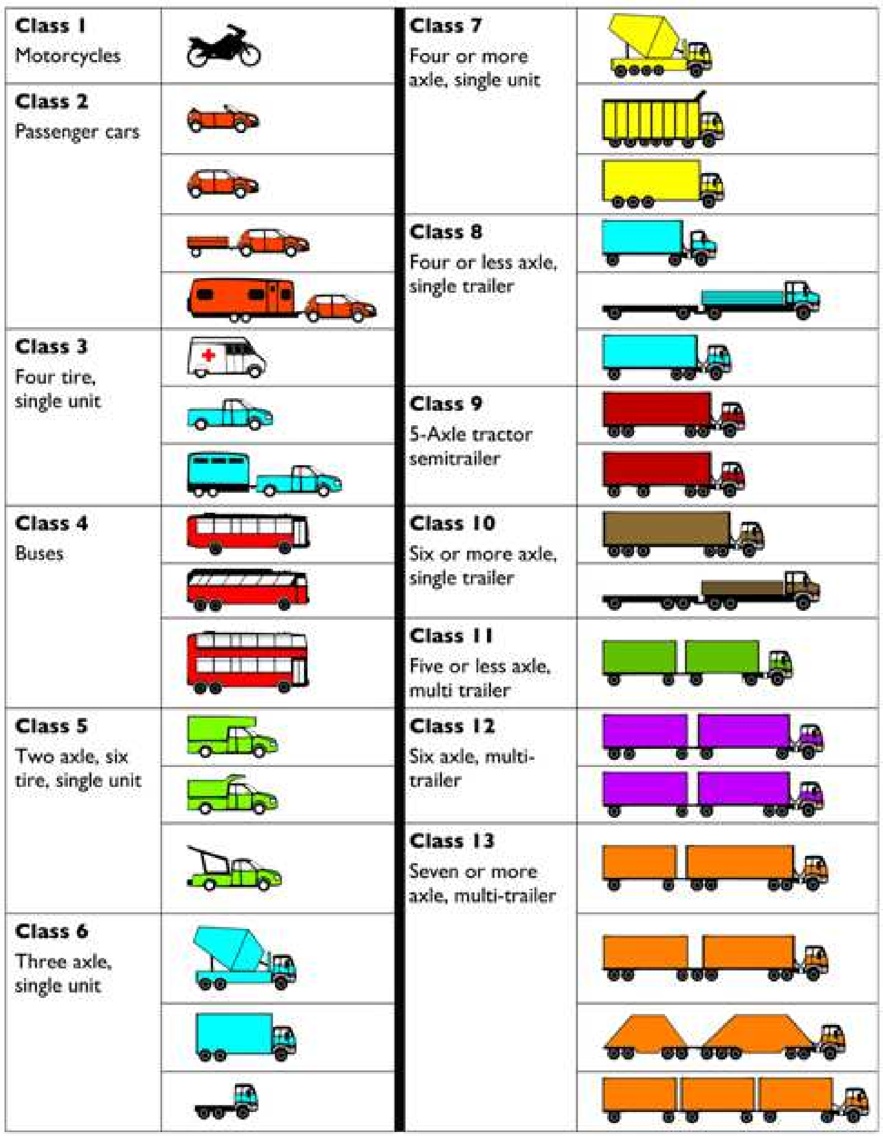

Figure 3.4: FHWA vehicle classifications

Decibel reading data

Using the sound level meter data and the corresponding video footage, the one-hour data sets were reviewed to determine decibel reading values and vehicle type for each passing vehicle.

The highest decibel reading was taken based on an approximate time window of three to five seconds during which the vehicle approached and then passed the sound level meter. As examples, four different scenarios where different vehicle types passed by the sound meters are shown in Figures 3.5 to 3.8.

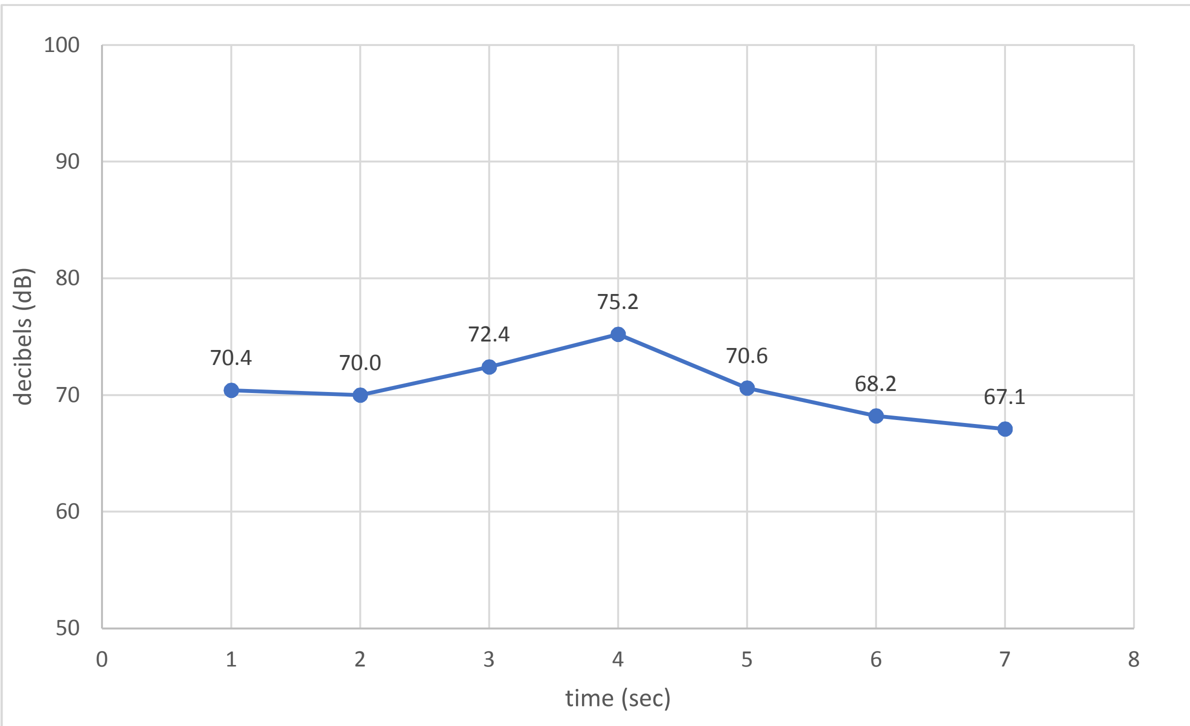

Figure 3.5: Sound meter recording of passenger vehicle without studded tires

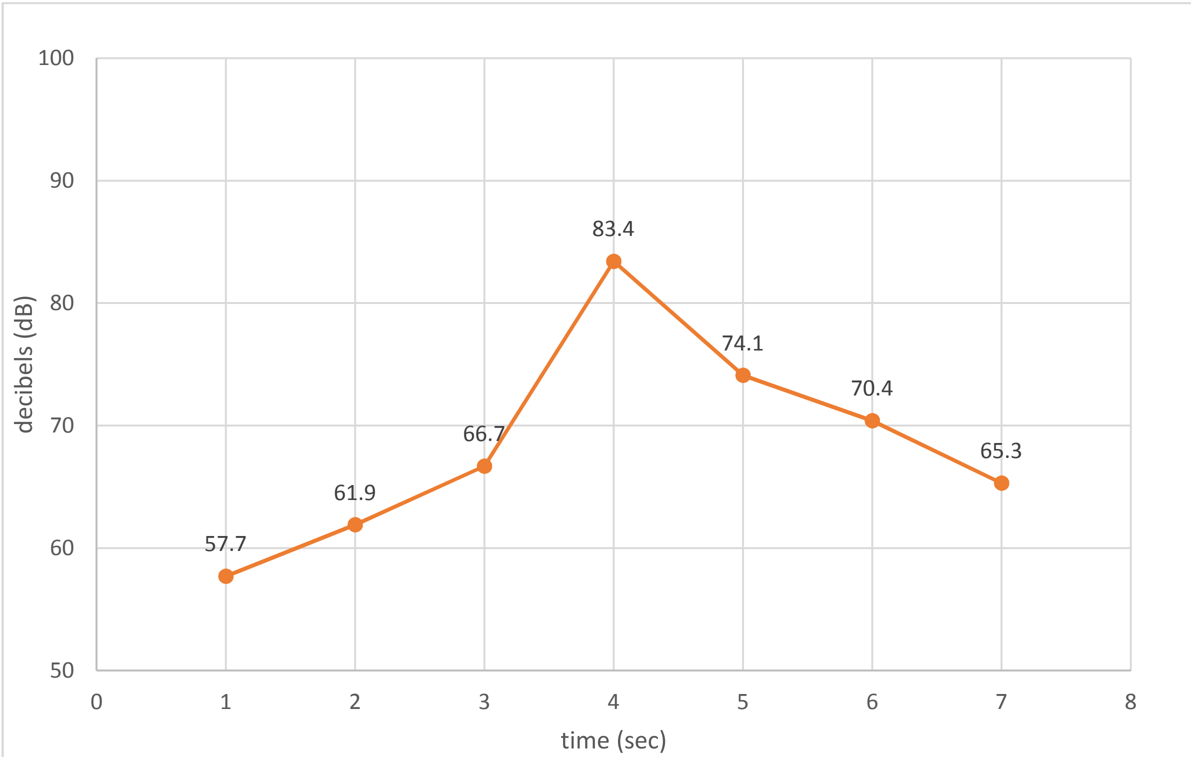

Figure 3.6: Sound meter recording of passenger vehicle with studded tires

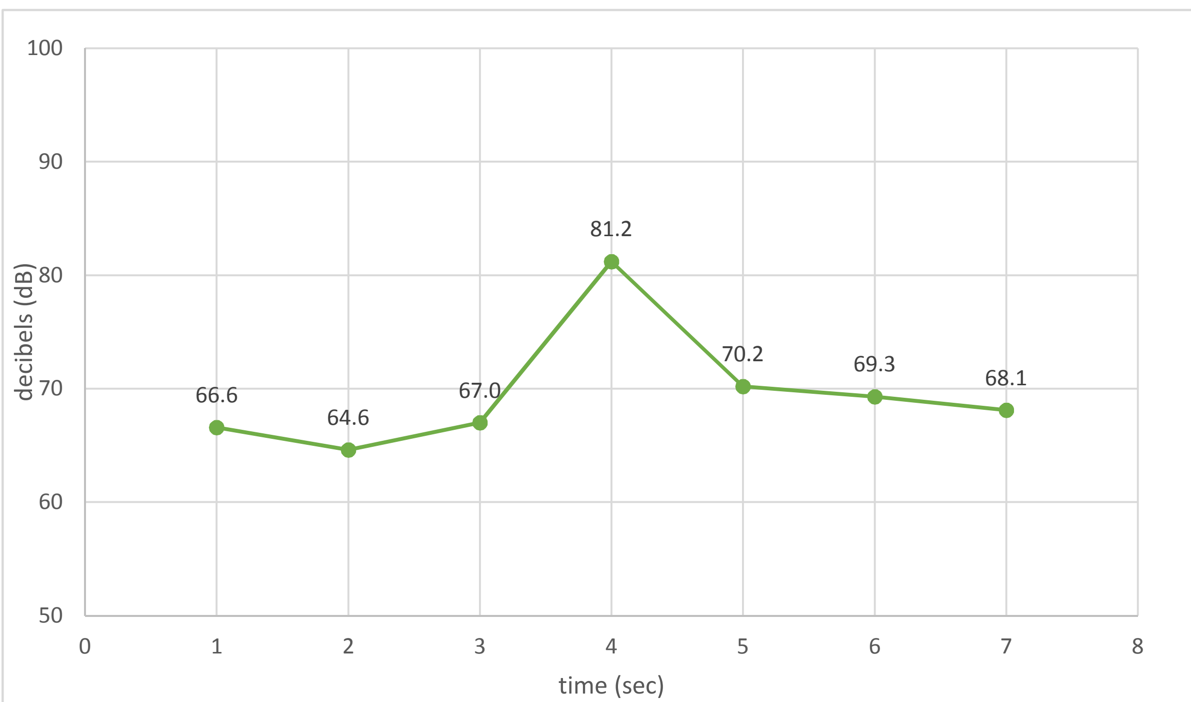

Figure 3.7: Sound meter recording of truck

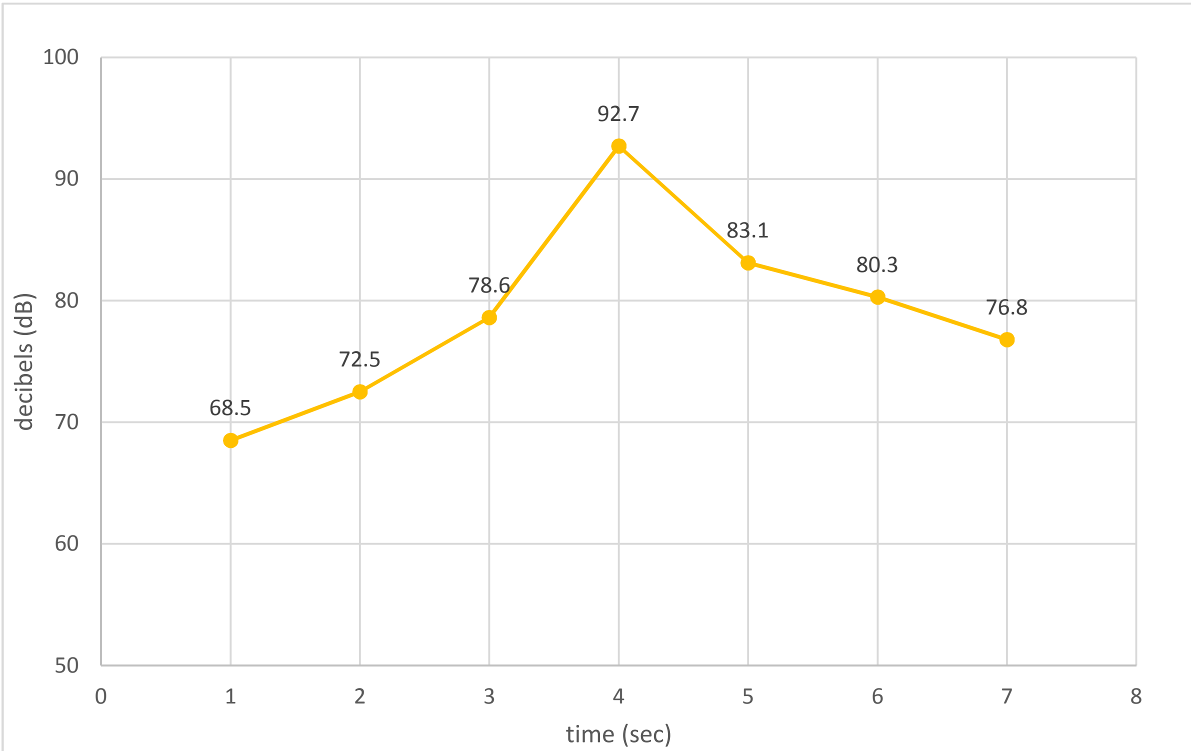

Figure 3.8: Sound meter recording of semi-truck

These figures illustrate how a representative decibel reading was chosen for each passing vehicle. For a single passing vehicle, one peak was present with lower decibel readings before and after the peak in most cases. Based on this pattern the highest decibel reading within the time span was used.

There were other observed scenarios when associating a decibel reading for each passing vehicle were more challenging. Some of these scenarios included two vehicles simultaneously passing by in different lanes and two or more vehicles consecutively passing by in the same lane. By synchronizing the video with the sound meter, it was easier to identify when a vehicle passed the sound meter and its approximate decibel reading.

Figure 3.9 represents a sound recording of two vehicles passing by the sound meter at almost the same instant, with one truck in the near lane (closer to the sound meter) and one passenger vehicle on the far lane. Some assumptions were made in order to analyze this data. Vehicles in the near lane and Class 9 and 10 vehicles were assumed to be louder. For instance, the highest decibel reading in Figure 3.9 was assumed to represent the truck passing by in the near lane, and the two data points that followed represented the passenger vehicle in the far lane.

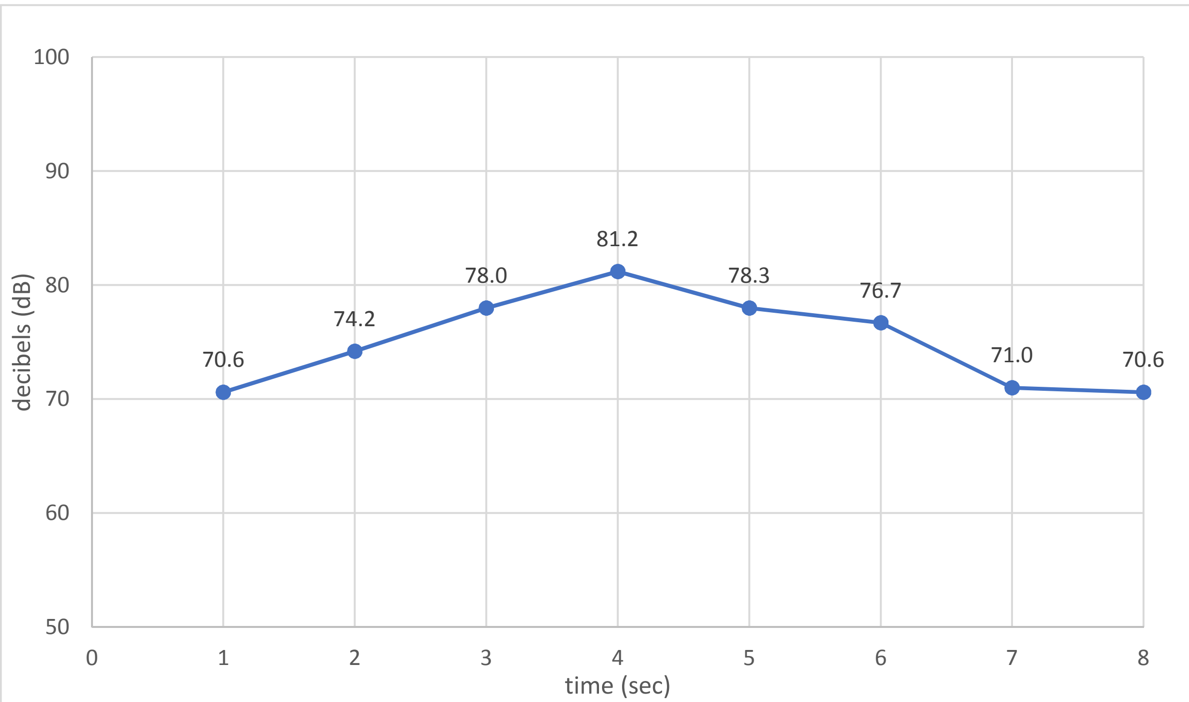

Figure 3.9: Example of two vehicles simultaneously passing sound meter

Figure 3.10 shows an example of three vehicles passing by within one to two seconds of each other. Based on the video, the first vehicle was a passenger vehicle in the far lane followed by a truck in the near lane and a passenger vehicle with studs in the near lane. The passenger vehicle with studs in the near lane recorded the highest decibel reading, and that point was used as a reference. By relying on the assumption that vehicles in the near lane were generally louder than those in the far lane, the second highest decibel reading was associated with the truck in the near lane.

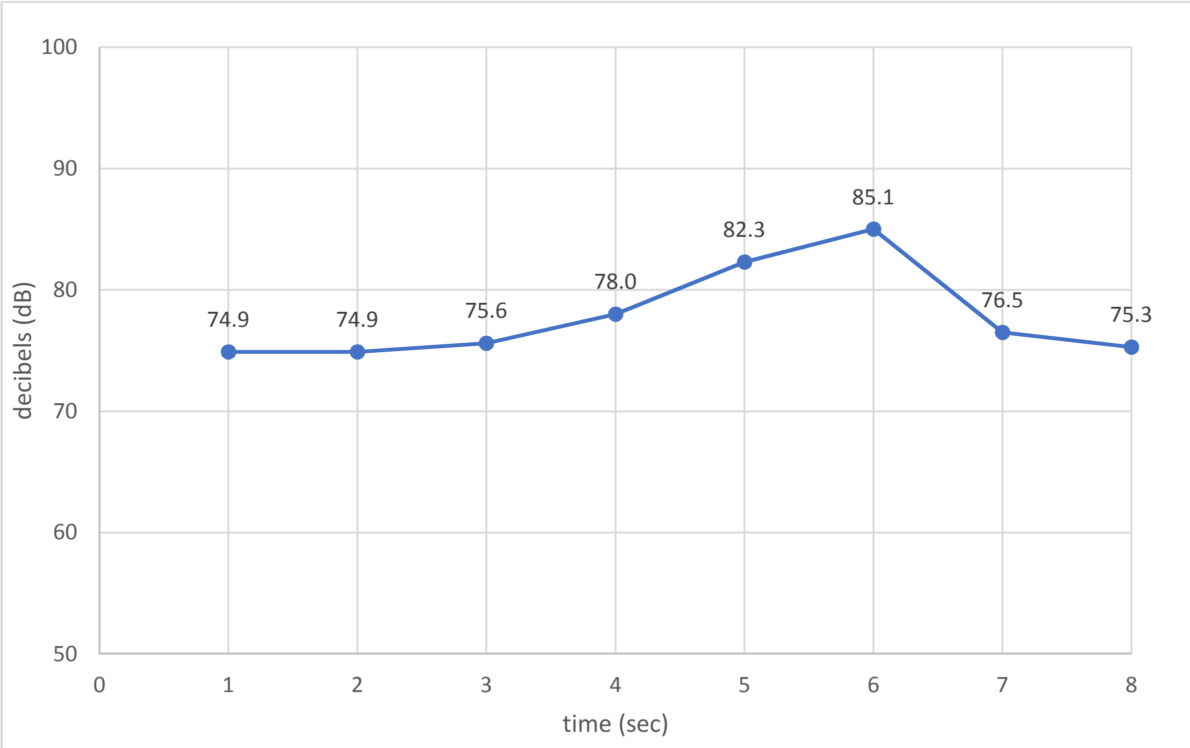

Figure 3.10: Example of multiple vehicles passing sound meter

Parking lot survey

To determine the percentage of vehicles with studded tires in the local area, a parking lot survey was conducted at several University of Idaho parking lots and the Eastside Marketplace, a small urban shopping complex, during the study period.

The specific University of Idaho parking lots included one of the largest parking lots (#60) on campus and other high traffic locations (i.e., Greek life parking). All of the parking lots shown in Figure 3.11 were visited for the parking lot survey. The totals from these parking lots were then combined into a larger representative sample.

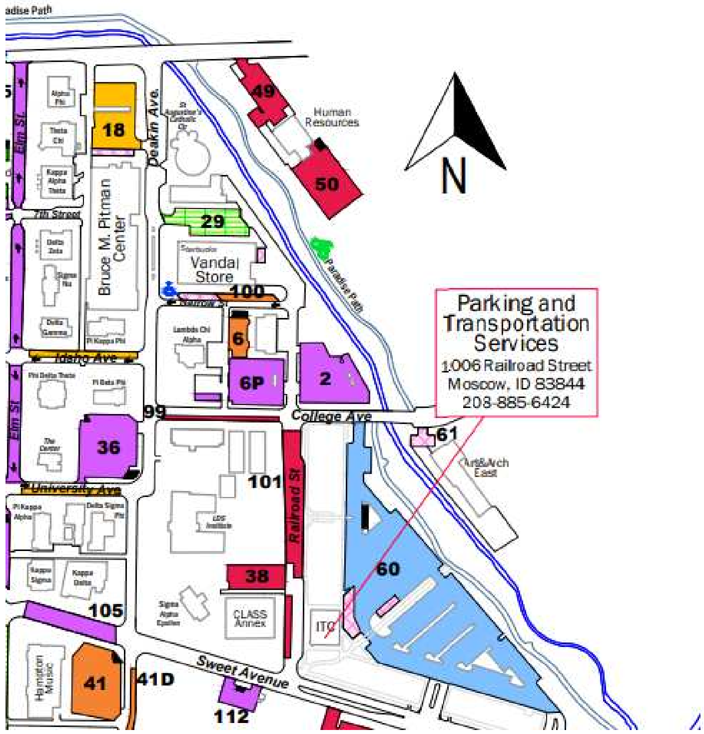

Figure 3.11: Part of the University of Idaho campus parking map

This study initially targeted parking lots at grocery stores, like WinCo, and commercial retailers, like Walmart. However, these locations did not allow the surveys to be performed due to store policy restrictions. As a result, other locations to perform the survey were considered. After contacting the Eastside Marketplace's manager, permission was given to perform the parking lot survey. The Eastside Marketplace is a shopping center with multiple restaurants, interaction spots for the community, and other shops. As shown in Figure 3.12, the parking lot to the right of the concrete divider (island in middle) was the area chosen for the survey and consisted of nine parking rows. The survey excluded the Safeway parking lot to avoid any policy issues with Safeway as previously experienced with WinCo and Walmart.

Figure 3.12: East side Marketplace parking lot

The surveys were performed manually by visual observation. The total number of vehicles was recorded along with vehicles that had installed studded tires. Vehicles with studded tires on either axle or both axles of the vehicle were counted equally. In other words, if a vehicle had studded tires installed on only the front or rear axle, it was considered equal to a vehicle with studded tires on both axles. The survey dates and vehicle counts are presented below in Table 3.1.

Table 3.1: Parking Lot Survey results

	Date	Vehicles	Vehicles with studs	% of vehicles with studs
Eastside Marketplace	Jan 8th 2021	69	20	28.9%
U of I	Feb 18th 2021	202	42	20.8%

The results from Table 3.1 showed that the overall usage percentage of studded tires from the two different surveys performed was 22.8%, representing 62 vehicles out of 271 vehicles. The results from this survey would be compared with the field data collected from the two highway locations.

ITD data collection stations

The Idaho Transportation Department has two ways of keeping highway traffic count records using automatic traffic recorders (ATR) and Weigh-In-Motion sensors (WIM). The automatic traffic recorders are roadside systems that use different sensors and electronics to record vehicle volume, length, speed, and classification data. According to ITD, there are approximately 175 ATRs located in the state of Idaho.

The automatic traffic recorders collect daily traffic for each month throughout the year. A monthly hourly traffic volume report was used to compare vehicle volumes with the results from this study. Volume data were available for each lane and for each hour. The southbound hourly lane volumes were used for US-95, and the westbound and eastbound lane volumes were used for ID-8. Figure 3.13 shows ITD’s automatic traffic recorder locations (#98 and #127) that were used for this study.

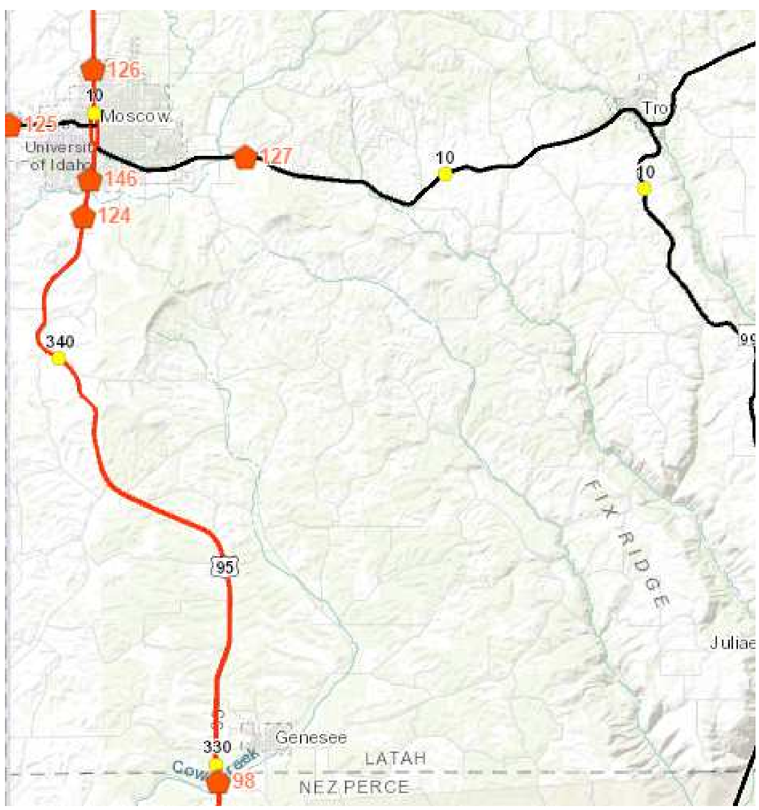

Figure 3.13: ITD's automatic recorder stations

The weigh in motion sensors collect weight data of vehicles, specifically axle weights to identify vehicle volume, and classification data. Monthly and specialty reports are available on ITD’s website. WIM reports were not used for this study.

Chapter 4: Results and Analysis

This chapter will begin by describing the results obtained from the data collection during the winter and summer seasons and summarize the decibel values of different vehicle types on both US-95 and ID-8. Two statistical t-tests comparing sound data collected during the two different seasons along with a comparison of passenger vehicles versus passenger vehicles with studs will then be presented. Next, an analysis of variance test was conducted to determine the effects of multiple variables on the data collection and multiple boxplots were created to illustrate these differences. Lastly, the outcomes from two prediction models will be used to forecast vehicle volumes and the likelihood probability of vehicles with studded tires.

In Table 4.1, the results from the winter and summer seasons along US-95 are provided based on the one-hour sound meter and video recordings. Table 4.2 summarizes similar data for ID-8. In addition to the average decibel reading for each category, a standard deviation was calculated along with the standard error which illustrated how far this sample mean deviated from the true sample mean. For emphasis purposes, the average decibel readings for the vehicles with studded tires have been italicized.

Table 4.1: US-95 Results, Winter vs. Summer

	Type	Lane	Sample size	Avg dB	st.deviation	error(±)
Winter	Pass veh	Far	22	76.3	2.54	0.80
	Pass veh	Near	25	80.7	2.43	0.49
	Pickup	Far	12	78.7	2.22	0.74
	Pickup	Near	37	82.4	3.46	0.84
	Other	Far	3	84.8	1.48	0.66
	Other	Near	7	86.3	4.59	1.73
	Veh W studs	Far	10	*79.2*	2.08	0.69
	Veh W studs	Near	23	*83.0*	2.74	0.57
		Total	139			

	Type	Lane	Sample size	Avg dB	st. deviation	error (±)
Summer	Pass veh	Far	68	76.3	2.91	0.65
	Pass veh	Near	75	81.7	3.69	0.67
	Pickup	Far	30	79.8	3.84	1.06
	Pickup	Near	50	85.5	4.61	1.06
	Other	Far	5	87.5	4.79	2.39
	Other	Near	10	95.7	4.43	1.48
		Total	238			

Win

Table 4.2:ID-8 Results, Winter vs. Summer

	Type	Direction	Sample size	Avg dB	st.deviation	error (±)
Winter	Pass veh	Far	19	75.7	1.91	0.44
	Pass veh	Near	38	82.7	2.89	0.47
	Pickup	Far	16	79.9	2.41	0.60
	Pickup	Near	20	84.8	3.61	0.81
	Other	Far	5	85.9	2.66	1.19
	Other	Near	8	91.4	3.54	1.25
	Veh W studs	Far	16	*80.7*	3.02	0.75
	Veh W studs	Near	30	*85.4*	3.94	0.72
		Total	152			
	Type	**Direction**	**Sample size**	**Avg dB**	**st.deviation**	**error (±)**
Summer	Pass veh	Far	158	74.8	3.18	0.25
	Pass veh	Near	67	79.4	3.38	0.41
	Pickup	Far	35	77.1	3.21	0.54
	Pickup	Near	42	80.8	3.76	0.58
	Other	Far	9	81.9	1.79	0.6
	Other	Near	9	87.9	2.77	0.92
		Total	320			

During the winter data collection period on US-95, there were 33 studded tire vehicles out of 139 vehicles which represented 23.7% of the sample size. Along ID-8, there were 46 studded tire vehicles out of 152 vehicles which represented 30.3% of the sample size. (For comparison purposes, the parking lot survey yielded 62 vehicles with studded tires out of 271 vehicles which represented 22.9% of the sample size.)

Two independent two-sample t-tests were conducted to evaluate the average decibel readings between the winter and summer results and between passenger vehicles with and without studded tires. The main assumption (i.e., null hypothesis) for this hypothesis testing was that the means of these data sets were equal. In other words, the test assumed that the mean for all winter data points did not vary from the mean of the summer data points, and also did not vary for passenger vehicles with and without studded tires. As a result of the t-tests, the null hypotheses were rejected. For both scenarios, the t-values were larger than the t-critical two-tail values.

Table 4.3:a) T-Test Comparing Winter vs. Summer b) T-Test Comparing Passenger Vehicles with (PWS) and without (Pass veh) Studded Tires

	t-test:Two-Sample assuming equal variances (95% confidence interval)					
	Sample size	**Mean**	**St.deviation**	**P-value**	**t-value**	**t-critical two tail**
Winter	257	82.5	19.9	9.84E-22	9.9	1.9
Summer	335	78.6	25.1	9.84E-22	-	-

a)

	t-test:Two-Sample assuming equal variances (95% confidence interval)					
	Sample size	**Mean**	**St.deviation**	**P-value**	**t-value**	**t-critical two tail**
PWS	72	82.7	12.5	8.85E-08	5.6	2.0
Pass veh	106	79.4	16.6	8.85E-08	-	-

b)

There was a significant difference between the winter (M=82.5, SD=19.9) and summer (M=78.6, SD=25.1, t (592) = 9.9) data sets. The t-value was greater than the t-critical two tail (1.9) which means a rejection to the null hypothesis that the two samples had equal variances. Passenger vehicles with studded tires (M=82.7, SD=12.5) also had a significant difference compared to passenger vehicles without studded tires (M=79.4, SD=16.6, t (178) = 5.6) with the t-value greater than the t-critical two-tail (2.0).

The main outcomes from these t-tests were that vehicles were collectively louder in the winter compared to the summer (likely attributed to the increase in studded tire vehicles), and passenger vehicles with studded tires were quantifiably louder than passenger vehicles without studded tires.

To further examine these results, a statistical analysis to calculate and summarize the variances of multiple variables was conducted using the R software package. In Figure 4.1, the average decibel reading for the different vehicle categories along both ID-8 and US-95 were examined. The figure lists vehicle types along the x-axis and dB (decibel units) along the y-axis. The vehicle types are passenger vehicles (P), pickup trucks (TR), passenger vehicles with studded tires (PWS), and other vehicles (O). Each boxplot is a vehicle type associated with a road. For instance, the third box plot from the left represents passenger vehicles with studs on ID-8. Each box plot represents

100% of the data, where 50% of the data lies within the box, and the upper and lower whiskers (dotted lines) represent maximum and minimum values, respectively. Outliers are noted with an open circle.

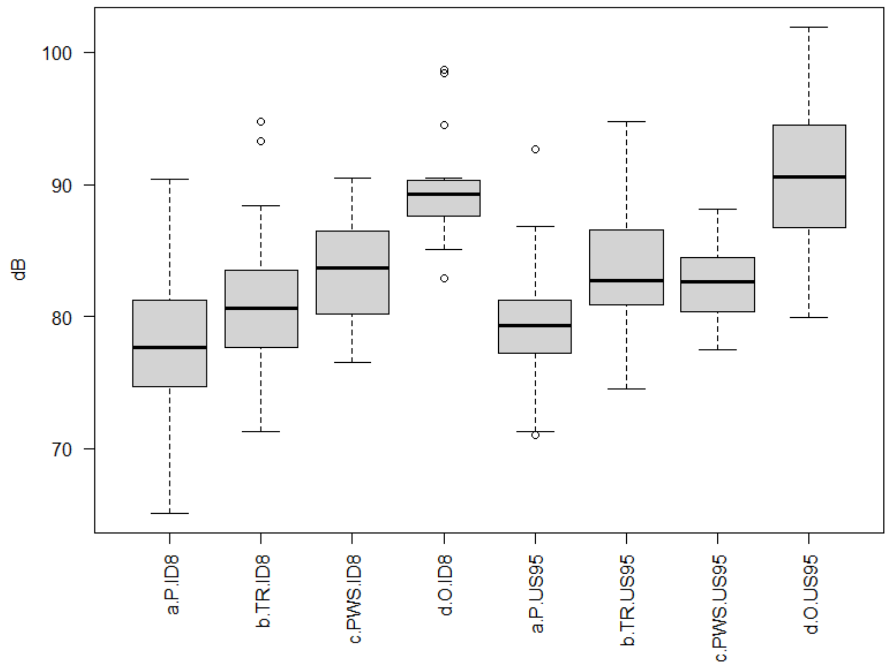

Figure 4.1: Effects of vehicle types and highway (i.e., ID-8 or US-95) location

Based on Figure 4.1, the "other" vehicle category recorded the highest decibel readings for both highways. The mean for the other (O) vehicles was 88.4 dB on ID-8 and 90.3 dB on US-95. Passenger vehicles with studs (PWS) were louder than pickup trucks (TR) on ID-8 but slightly quieter on US-95. The mean for PWS on ID-8 was 84.9 dB and 83.3 dB on US-95. The means for pickup trucks were 81.1 dB on ID-8 and 83.8 dB on US-95. Finally, passenger vehicles (P) had a mean of 78.3 dB on ID-8 and 78.8 dB on US-95.

Another analysis examined the effects of lane proximity. In Figure 4.2, the results show that vehicles traveling along the far lane were recorded to have a lower decibel reading when compared with vehicles traveling in the near lane.

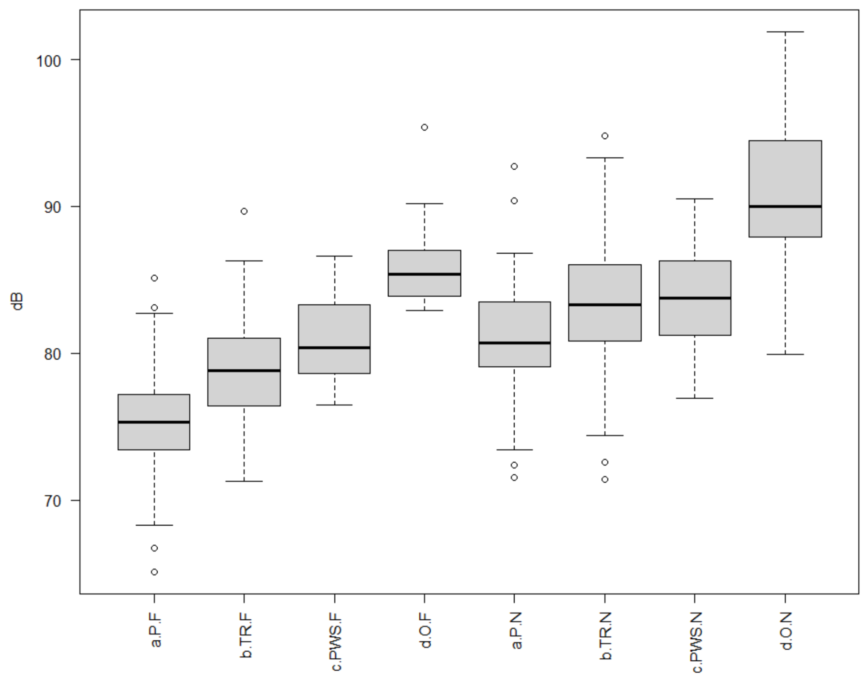

Figure 4.2:Effects of vehicle type and lane position

The relative distance from the sound level meter to the vehicle based on travel lane resulted in a noticeable difference in the decibel readings. For this study, all travel lanes were twelve feet in width and the sound meters were placed approximately five feet away from the fog line (i.e., white edge lane marking) of the nearest lane.

Passenger vehicles with studded tires had a mean of 84.7 dB in the near lane, and 82.6 dB in the far lane. By comparison, passenger vehicles (P) averaged 80.3 dB for the near lane and 74.6 dB for the far lane. Pickup trucks (TR) averaged 83.1 dB and 77.6 dB for the near and far lanes, respectively, and other vehicle types (O) averaged 91.9 dB in the near lane and 87.3 dB in the far lane.

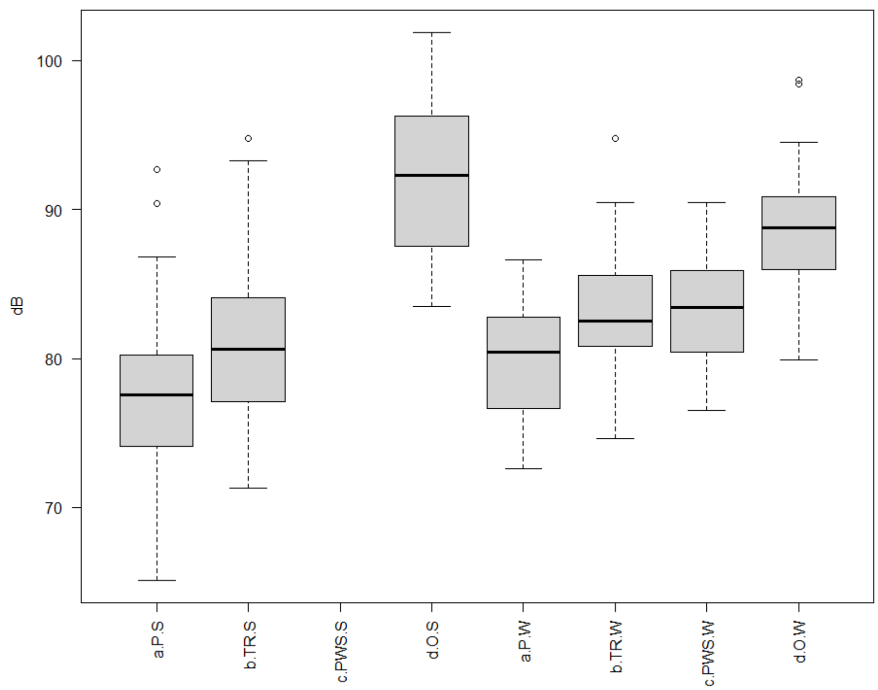

Figure 4.3:Effects of vehicle type and season

Figure 4.3 describes the decibel readings of different vehicle types based on whether the data were collected in the winter or summer. Passenger vehicles with studded tires collectively averaged 82.6 dB. No data for this category, of course, were collected during the summer months. By comparison, passenger vehicles without studded tires had a mean of 77.7 dB in the summer and a mean of 81.6 dB in the winter, pickup trucks had means of 82.3 dB in the summer and 83.7 dB in the winter, and other vehicle types had means of 92.1 dB in the summer and 89.5 dB in the winter.

An analysis of variance (ANOVA) was conducted to observe the significance of variance between the main variables (first order effect) and the main variables associated with other factors (second order effect). Tables 4.4 and 4.5 show the variables used for this test along with the ANOVA results. In other words, the analysis of variance tested whether the effects of vehicle type, lane, season, or highway had differences in their mean decibel levels. The ANOVA also tested for interactions among the factors in which the effects of one factor changed depending on the level of another factor.

Table 4.4:Analysis of variance (ANOVA) variables

Variable	Description
Vtype	Vehicle type (Passenger, Pickup (Truck), Passenger with studs, Other)
Lane	Lane being either close or far
Season	Winter and summer
Road	US-95 and ID-8
Vtype:Lane	Vehicle type associated with Lane (close or far)
Vtype:season	Vehicle type associated with Season (Winter or summer)
Vtype:Road	Vehicle type associated with Road
Season: Road	Season associated with road

Table 4.5:Analysis of variance (ANOVA) results

Variable	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Vtype	3	5679.2	1893.1	155.3	< 2.2e-16
Lane	1	3305.4	3305.4	271.2	< 2.2e-16
Season	1	95.3	95.3	7.8	0.005346
Road	1	36.3	36.3	3.0	0.084796
Vtype:Lane	3	103.6	34.5	2.8	0.037708
Vtype:Season	2	181.4	90.7	7.4	0.000645
Vtype:Road	3	99.9	33.3	2.7	0.043088
Season:Road	1	354.4	354.4	29.1	1.02E-07
Residuals	574	6996.2	12.2		

This model analyzed factors instead of independent variables, main effects instead of one-way effect variables, and interaction effects instead of two-way effect variables. The null hypothesis assumed that these independent variables would have no effect on the dependent variable. For instance, the null hypothesis for the first variable (Vtype) was that all vehicle types had equal average decibel readings, and the p-value was used to either accept or reject the hypothesis. The first four variables were one-way effect variables and the second four were two-way effect variables.

Based on the analysis, interactions between vehicle type and lane (p-value=0.0377), vehicle type and season (p-value=0.001), vehicle type and road (p-value=0.043), and season and road (p-value=1.02E-07) were all significant since their values were less than 0.05. In addition, the independent variables of vehicle type, lane, and season were also significant. These results showed whether there was or was not a significant effect, in other words this meant that vehicle types based on which lane they were in affected the data’s variance, and results differed from each other. This premise applied to the other variables explored, as the data collected were different based on vehicle type and season. The code for the ANOVA analysis is provided in Appendix B.

Prediction model

The prediction model used a special package in R to extract "features" from a smoothed curve based on discretely sampled functional data. Decibel readings over time were considered discretely sampled data in this case. The model extracted key features such as the mean, first and second derivatives, critical points (i.e., local maxima and minima), and outliers. The model counted specific elements including the number of critical values with above average decibel values, and the negative second derivatives represented by local maxima. Figure 4.4 to 4.7 illustrate the analysis steps performed by the R prediction model using a 100 second sample data set. This same process was applied to the seven-hour data sets which consisted of approximately 25,000 decibel readings each.

The prediction model first plotted all the decibel readings for a specific data set. Figure 4.4 shows the decibel readings for the 100 second data set used as an initial test. The x-axis represents the time a reading was recorded, and the y-axis represents its decibel value.

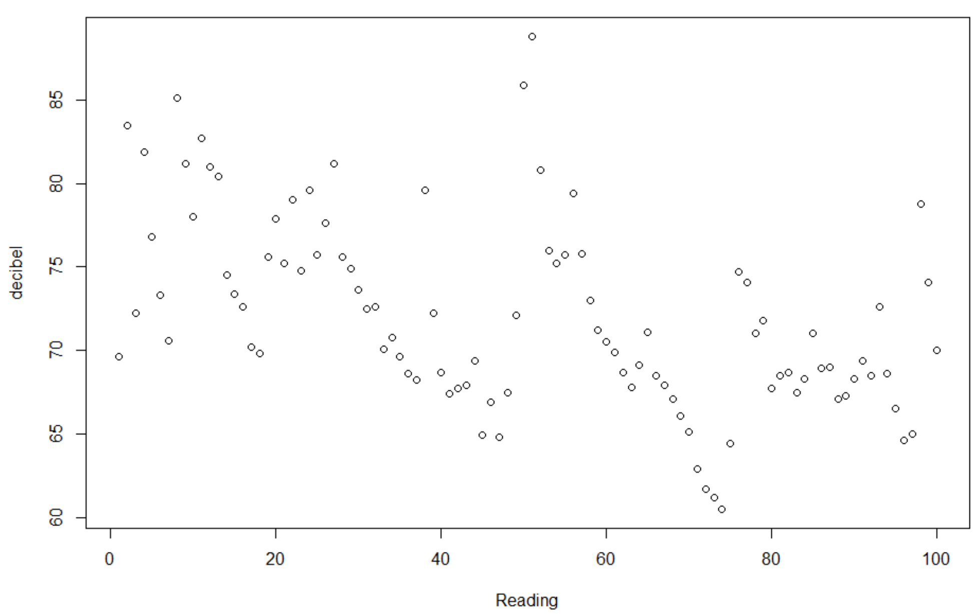

Figure 4.4: Prediction model plotted data readings

The model then fit a function with a smooth curve to the decibel readings based on the observed pattern (see Figure 4.5).

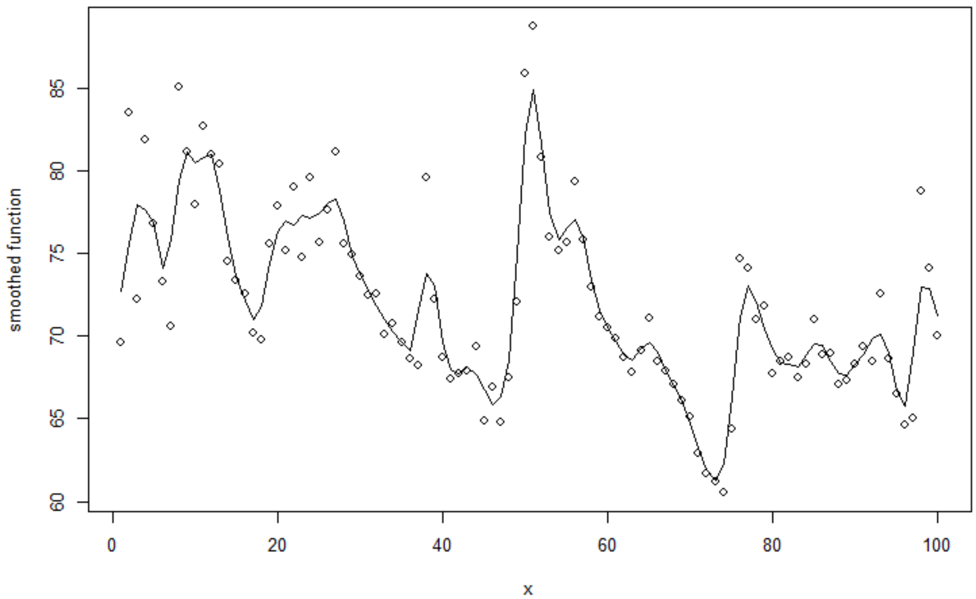

Figure 4.5: Prediction model fitted function is first smoothed

Finally, the model extracted features of the smoothed function which included the first and second derivatives, mean values, and critical points. The first derivative identified points on the dotted line shown in Figure 4.6. The second derivative used the points initially identified to find the local maxima shown in Figure 4.7.

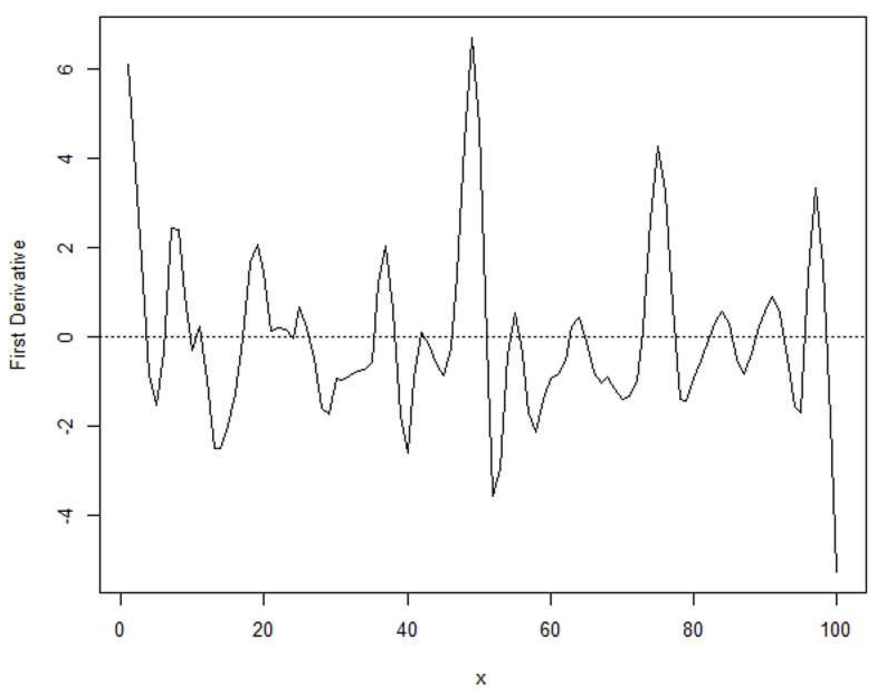

Figure 4.6: First derivatives from smooth function

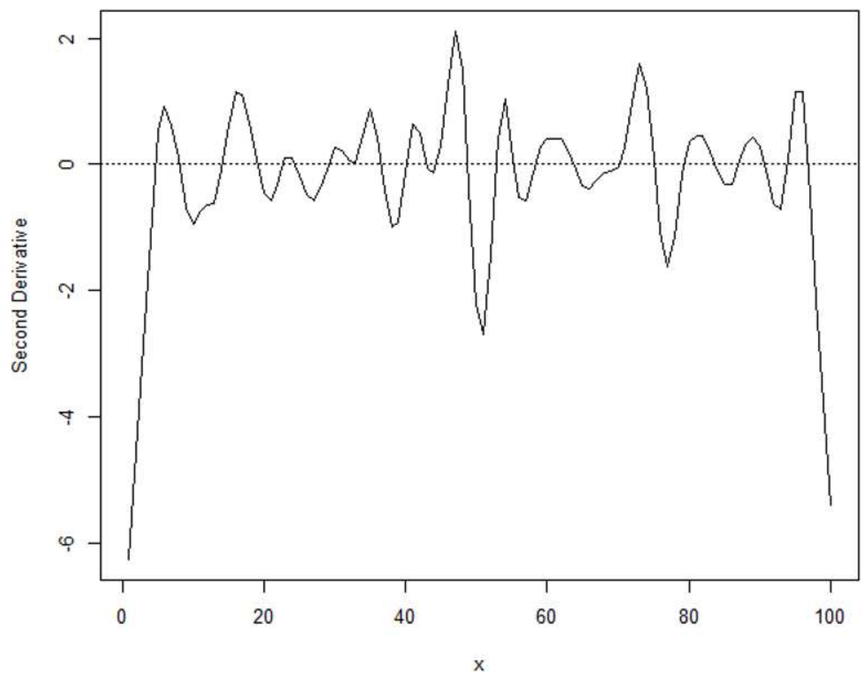

Figure 4.7: Second derivative from smooth function

This method was used to estimate the number of vehicles passing by the sound meter. This result was then compared with ITD ATR data.

Table 4.6 shows the results from the prediction model and the ITD results for each road and season. The US-95 prediction model underestimated by 42 vehicles using winter data which represented a 3.2% error rate and underestimated by 255 vehicles using summer data resulting in a 15.5% error rate. The winter data from ID-8 was the only scenario where the model overestimated the vehicle volumes (15.4% error). The summer data for ID-8 underestimated vehicle volumes by 74 vehicles for a 5.2% error.

Table 4.6: Comparison of prediction model with ITD results

	Vehicle Volumes		
Road/season	**Prediction model results**	**ITD results**	**Error %**
US-95/Winter	1270	1312	3.2%
US-95/Summer	1390	1642	15.3%
ID-8/Winter	1421	1231	15.4%
ID-8/Summer	1342	1416	5.2%

The error percentages were calculated using the predicted model results and the recorded ITD volume results using this equation:

$$Absolute\ percentage\ error = \left|\frac{Actual - predicted}{Actual}\right| * 100$$

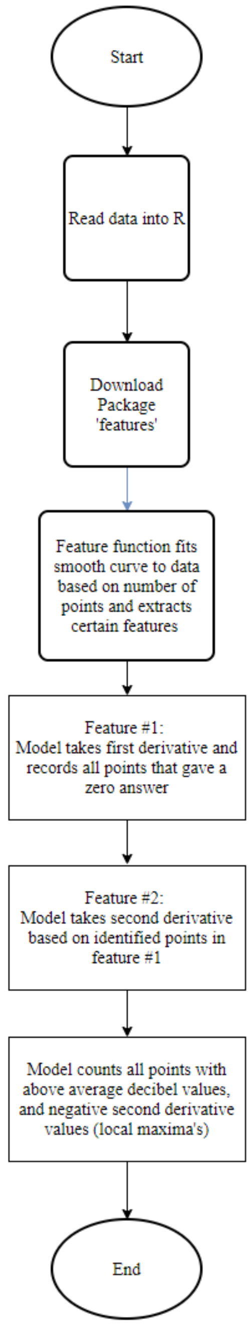

Figure 4.8: Flowchart of vehicle volume prediction model

Probability likelihood

To associate a probability likelihood for vehicle types based on the different decibel ranges, a multinomial logistic regression was performed in R. This model used an algorithm to predict categorical variables, which was the vehicle type in this study. The model used explanatory variables (i.e., characteristics) to identify the possible outcomes and their probabilities. The characteristics in this study were the different vehicle types and their average decibel readings. The multinomial logistic regression model used the rule that all probabilities for a specific outcome must equal one, and this was carried out and applied for each decibel reading range.

Likelihood probabilities for each vehicle type based on decibel readings were generated based on the winter data sets when vehicles with studded tires were present.

Probabilities for vehicle types falling in the same decibel range and being in either the near or far lane were combined. The prediction model only predicted vehicle type based on a decibel reading but could not associate with a particular lane. These likelihood probabilities are shown in Table 4.7.

Table 4.7: Likelihood probabilities

Decibel range	Passenger vehicle	Pickup	Passenger vehicle with studs	Other
70-75 dB	0.90	0.05	0.05	0.00
75-80 dB	0.58	0.22	0.19	0.01
80-85 dB	0.26	0.36	0.31	0.07
85-90 dB	0.04	0.34	0.30	0.32
90 dB and above	0.00	0.14	0.13	0.73

The dominant probability for the 70 to 75 dB decibel range was the passenger vehicles category at 90%, and all other categories had a significantly lower probability. The highest probability that a vehicle type was in the 75 to 80 dB range remained the passenger vehicle category but there was a rise in probabilities for the pickup and passenger vehicle with studs categories while the other category remained low. The pickup category was the highest probability in the 80 to 85 dB range followed by passenger vehicles with studs. This decibel range was where passenger vehicles with studs was most likely to occur. The pickup category also dominated the 85 to 90 dB range with the highest probability and was followed by the passenger vehicle with studs category. In the highest decibel range, the probability was dominated by other vehicles and there was still a small presence for pickups and passenger vehicles with studs. As seen in Table 4.7, passenger vehicle with studs tended to mirror the decibel ranges of pickups.

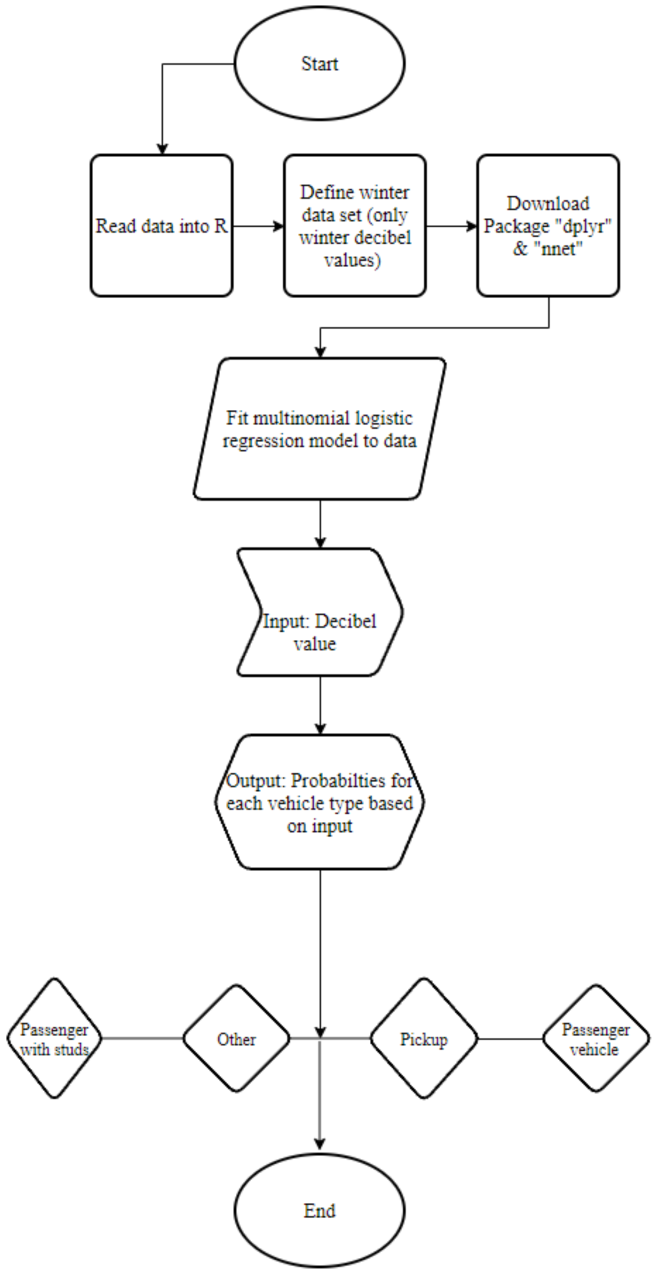

Figure 4.9: Flowchart of vehicle type prediction model

Table 4.8 represents a summary of studded tire vehicle percentages for the different methods used in this study. Parking lot surveys were added together to obtain their total percentage. Video recording percentages were represented by the one-hour data sets during the winter season. The studded tire vehicle percentages using the prediction model, based on the likelihood probability values were calculated using the following equation:

$$Studded\ tire\ vehicle\ \% = \frac{V_v\ *\ L_p}{P_d} * 100$$

Where:

V_v : Predicted vehicle volume for a decibel range

L_p: Likelihood probability for a decibel range

P_d: Predicted total vehicle volume from prediction model

The parking lot surveys and video recordings had similar studded tire vehicle percentages although the parking lot surveys had a larger vehicle volume compared to the video recordings. The prediction model results were also similar to the other methods but represented significantly more vehicle volumes. The code for the logistic regression model and some variable coefficients is provided in Appendix C.

Table 4.8: Summary of studded tire vehicle percentages

Method	Location	Total vehicles	Studded tire vehicle percentages
Parking lot surveys	All locations together	271	22.9%
Video recordings	US-95	139	23.7%
Video recordings	ID-8	152	30.3%
Prediction model	US-95	1270	14.2%
Prediction model	ID-8	1421	23.9%

As described earlier, the measured studded tire vehicle percentage on US-95 for one hour during the winter was 23.7%, based on 33 studded tire vehicles out of 139 total vehicles. The prediction model concluded that 14.2% of the vehicles on US-95 had studded tires, which represented approximately 180 out of 1270 total vehicles. The model also concluded that 23.9% of the vehicles on ID-8 had studded tires, which represented approximately 340 out of 1421 total vehicles.

Assuming overestimation, this could be possible since ID-8 had two lanes in opposite directions compared to US-95 lanes meaning there could have been more overlapping vehicles which contributed to more critical points the model counted (see Table 4.6).

Chapter 5: Conclusions

This research explored a method of collecting sound data to quantify studded tire volumes on highways and to differentiate between drivers who had installed studded tires on their vehicles with those who had not. Based on the results collected from an off-the-shelf sound meter device used in this research, it was apparent that while vehicles with studded tires generate a higher decibel reading when matched with comparable vehicles, the decibel reading alone could not be used to definitively determine whether or not a vehicle was using studded tires. The reason is because the decibel reading of certain pick-up trucks and semi-trucks were comparable to passenger vehicles with studded tires. For this reason, a secondary and complementary method such as video capture of the travel environment or a field observer was required for this method to be reliably used. A prediction model presented in this study used the sound patterns observed from the data collected to approximate and differentiate vehicle types.

This study quantified several expected findings, including higher overall decibel readings in the winter versus the summer, and noticeable differences in the decibel readings depending on whether a vehicle was traveling in the lane nearest the sound meter or one lane width away in the far lane. Based on the analysis of variance, this study concluded that the interactions between a particular vehicle type and lane, season, or highway were statistically significant.

Analyzing specific frequency levels is recommended for future studies as that factor could help differentiate studded tires from other vehicles. This study only used the sound pressure levels as the differentiating factor. There are more advanced sound meters available that could be used to analyze the frequency spectrum of the sound recordings which are also recommended here. One of the challenges faced in this research was separating vehicles in the analysis when two or more vehicles passed the sound meters instantaneously and looking closely at sound patterns is recommended.

The results from both prediction models showed that sound data can be utilized to approximate both vehicle volumes and studded tire vehicle volumes. The accuracy for predicting vehicle volumes proved to be better than predicting exclusively studded tire vehicles. The reason was attributed to studded tire vehicles overlapping with pickups in terms of decibel values. It was concluded from the probability likelihood values that vehicles with studded tires frequently fell in the 80 to 85 dB range. The vehicle volume prediction model had similar results to actual field volumes recorded by ITD, and the only overestimation occurred using the ID-8 winter data set. Since ID-8 had two lanes with opposite traffic movement could have possibly led vehicles to overlapping frequently which made the sound meters record more higher decibel readings, which contributed to an overall higher average decibel reading which the prediction model uses.

There is inherent value to determining the actual studded tire vehicle volumes on each highway. As noted earlier, the wear and tear on the roadway surface that is caused by studded tire usage is not insignificant over time and providing detailed information to state departments of transportation can help to enhance life cycle cost analysis on specific facilities. While parking lot and phone surveys can be used to yield general results, site-specific data, when available, is desired. While more sophisticated and potentially cost prohibitive sound meter devices could be used to refine the data collection method, the authors believe that field observations at present may, in fact, be most appropriate when quantifying on-site studded tire vehicle volumes along key highway locations.

Appendix A: Idaho and Washington studded tire legislations

Idaho (Idaho Statutes, TITLE 49 MOTOR VEHICLES, 49-948, Restriction as to tire equipment)/ Washington (Washington State Legislature, WAC 204-24-030, Standards for studded tires):

(1) Every solid rubber tire on a vehicle shall have rubber on its entire traction surface at least one inch thick above the edge of the flange of the entire periphery.

(2) No person shall operate or move on any highway any motor vehicle, trailer, or semitrailer having any metal tire in contact with the highway.

(3) No tire on a vehicle moved on a highway shall have on its periphery any block, stud, flange, cleat, spike, or any other protuberance of any material other than rubber which projects beyond the tread of the traction surface of the tire, except as allowed herein. It shall be permissible to use farm machinery with tires having protuberances which will not injure the highway, and it shall be permissible to use tire chains. Tires with built-in lugs of tungsten carbide or other suitable material, hereinafter called studs, may be used upon any vehicle when required for safety because of snow, ice, or other conditions tending to cause a vehicle to skid, that will not unduly damage the highway. Motor vehicles, trailers and semitrailers with tires having built-in studs are prohibited on public highways between the dates of May 1 and September 30, annually, except as provided in paragraphs (a), (b) and (c) of this subsection:

(a) Fire pumper/tanker trucks and ladder trucks belonging to fire departments and firefighting agencies are exempt from the prohibited dates.

(b) A vehicle may be equipped year-round with tires that have retractable studs if the studs retract pneumatically or mechanically to at or below the wear bar of the tire when not in use and the retractable studs protrude beyond the wear bar of the tire only between October 1 and April 30. Retractable studs may be made of metal or other material and are not subject to the stud weight requirements of subsection (4) of this section.

(c) Special exemptions from the prohibited dates may be granted by the Idaho transportation board if it is found by the board that enhancements to public safety outweigh the increased pavement wear.

(4) Commercial tire retailers shall not sell studded tires with studs exceeding the following weight and protrusion limitations after July 1, 2005. Commercial tire retailers and tire shops

shall not manually install studs exceeding the following weight and protrusion limitations after July 1, 2005.

(a) Studs shall not protrude more than six-hundredths (.06) of an inch from the surface of the tire tread when originally installed.

(b) Stud size shall be as recommended by the manufacturer of the tire for the type and size of the tire.

(c) Studs shall individually weigh no more than one and one-half (1.5) grams if the stud is size 14 or less.

(d) Studs shall individually weigh no more than two and three-tenths (2.3) grams if the stud size is 15 or 16.

(e) Studs shall individually weigh no more than three (3) grams if the stud size is 17 or larger.

(5) If the Idaho transportation department determines, at any time, that Lookout Pass or Fourth of July Pass on interstate 90 or Lolo Pass on state highway 12 is of an unsafe condition so as to require chains, as defined in section 49-104, Idaho Code, in addition to pneumatic tires, the Idaho transportation department may establish requirements for the use of chains on all commercial vehicles as defined in section 49-123(2)(d)(i) and (ii), Idaho Code, traveling on interstate 90 or state highway 12. If the Idaho transportation department establishes that chains are so required, the Idaho transportation department shall:

(a) Provide multiple advance notices of the chain requirement;

(b) Provide adequate opportunities for pull out;

(c) Provide notification at a point at which the commercial vehicle can safely pull out of the normal flow of traffic, prior to the point at which chains are required; and

(d) In no case post requirements for chains on bare pavement.

(6) Provided that the conditions in subsection (5) of this section are met, the chain requirement shall be met by chaining a minimum of one (1) tire on each side of:

(a) One (1) drive axle, regardless of the number of drive axles; and

(b) One (1) axle at or near the rear of each towed vehicle. Such axle shall not include a variable load suspension axle or an axle of a converter dolly.

(7) Chains as required in subsection (6)(a) and (b) of this section mean "chains" as defined in section 49-104, Idaho Code. Any other traction device differing from chains in construction, material or design but capable of providing traction equal to or exceeding that of chains under similar conditions may be used.

(8) The Idaho transportation department shall place and maintain signs and other traffic control devices on the interstate and state highway passes as designated in subsection (5) of this section that indicate the chain requirements under subsection (6) of this section.

(9) Exempt from the chaining requirements provided for in subsections (5) and (6) of this section are:

(a) Motor vehicles operated by the Idaho transportation department when used in the maintenance of the interstate or state highway system; and

(b) The following:

(i) Motor vehicles employed solely in transporting school children and teachers to or from school or to or from approved school activities, when the motor vehicle is either:

1. Wholly owned and operated by such school; or

2. Leased or contracted by such school and the motor vehicle is not used in furtherance of any other commercial enterprise;

(ii) Motor vehicles controlled and operated by any farmer when used in the transportation of the farmer's farm equipment or in the transportation of supplies to the farmer's farm;

(iii) The transportation of agricultural products at any time of the year;

(iv) Motor propelled vehicles for the sole purpose of carrying United States mail or property belonging to the United States;

(v) Motor carriers transporting products of the forest at any time of the year, including chip trucks;

(vi) Motor carriers transporting products of the mine including sand, gravel and aggregates thereof, excepting petroleum products; and

(vii) Vehicles properly equipped, designed and customarily used for the transportation of disabled or abandoned vehicles by means of a crane, hoist, tow bar, dolly or roll bed, commonly known as a "wrecker truck" or "tow truck."

Washington State legislations for studded tire are as following:

(1) It is unlawful to operate a vehicle upon the public highways of this state unless it is completely equipped with pneumatic rubber tires except vehicles equipped with temporary-use spare tires that meet federal standards that are installed and used in accordance with the manufacturer's instructions.

(2) No tire on a vehicle moved on a highway may have on its periphery any block, flange, cleat, or spike or any other protuberance of any material other than rubber which projects beyond the tread of the traction surface of the tire, except that it is permissible to use farm machinery equipped with pneumatic tires or solid rubber tracks having protuberances that will not injure the highway, and except also that it is permissible to use tire chains, alternative traction devices, or metal studs imbedded within the tire of reasonable proportions and of a type conforming to rules adopted by the state patrol, upon any vehicle when required for safety because of snow, ice, or other conditions tending to cause a vehicle to skid. It is unlawful to use metal studs imbedded within the tire between April 1st and November 1st, except that a vehicle may be equipped year-round with tires that have retractable studs if:

(a) The studs retract pneumatically or mechanically to below the wear bar of the tire when not in use; and

(b) the retractable studs are engaged only between November 1st and April 1st. Retractable studs may be made of metal or other material and are not subject to the lightweight stud weight requirements under RCW 46.04.272. The state department of transportation may, from time to time, determine additional periods in which the use of tires with metal studs imbedded therein is lawful.

(3) The state department of transportation and local authorities in their respective jurisdictions may issue special permits authorizing the operation upon a highway of traction engines or tractors having movable tracks with transverse corrugations upon the periphery of the movable tracks or farm tractors or other farm machinery, the operation of which upon a highway would otherwise be prohibited under this section.

(4) Tires with metal studs imbedded therein may be used between November 1st and April 1st upon school buses and fire department vehicles, any law or regulation to the contrary notwithstanding.

Additional standards for studded tires in Washington:

(1) Studs must be metal, tipped with tungsten carbide.

(2) Metal studs must be inserted only in a new tire or a newly-recapped tire which has molded in the tread the "pin-holes" into which metal studs are to be inserted. Studs must not be inserted in any new tire or newly-recapped tire after it has been driven on a vehicle.

(3) Metal studs may be installed only by the tire manufacturer, or by a tire dealer or tire jobber who shall install the metal studs in conformance with the manufacturer's specifications.

(4) When a tire is sold or offered for sale as a studded tire or when studs are installed in a new tire or a newly recapped tire, there must be a minimum of seventy metal studs evenly spaced around the tread of the tire.

(5) A tire must contain a minimum of fifty-six metal studs at all times in order to qualify as a "studded tire" or as an approved traction device.

(6) Metal studs must not be installed in any tire of a vehicle which has a gross vehicle weight of ten thousand pounds or over.

(7) School buses and fire department equipment tires are exempt from subsection (6) of this section.

Appendix B: ANOVA analysis code

```
#ANOVA Analysis

#Note: Road2 is the name of the file which can be changed on the user’s
preference

Road2 <- read.csv("c:/temp/Meeloud2.csv",header=TRUE)
head(Road2)

names(Road2)

table(Road2$Lane,Road2$Season)
table(Road2$Vtype,Road2$Season)


boxplot(Dec ~ Vtype*Road, data=Road2, las=2, xlab="",ylab="dB")
par(mar=c(8, 4.1, 4.1, 2.1))

boxplot(Dec ~ Vtype*Lane, data=Road2, las=2, xlab="",ylab="dB")
par(mar=c(8, 4.1, 4.1, 2.1))

boxplot(Dec ~ Vtype*Season, data=Road2, las=2, xlab="",ylab="dB")


Road2$Vtype  <- as.factor(Road2$Vtype)
Road2$Lane  <- as.factor(Road2$Lane)
Road2$Season  <- as.factor(Road2$Season)
Road2$Road  <- as.factor(Road2$Road)

RoadDec.lm1 <- lm(Dec ~ (Vtype+Lane+Season+Road)^2, data=Road2)
anova(RoadDec.lm1)

RoadDec.lm2 <- lm(Dec ~ Vtype+Lane+Season+Road+
                    Vtype:Lane +Vtype:Season +Vtype:Road +Season:Road,
                  data=Road2)
anova(RoadDec.lm2)

interaction.plot(Road1$Vtype,Road2$Lane,Road1$Dec,type="b")
interaction.plot(Road1$Vtype,Road2$Season,Road1$Dec,type="b")
interaction.plot(Road1$Vtype,Road2$Road,Road1$Dec,type="b")
interaction.plot(Road1$Season,Road2$Road,Road1$Dec,type="b")
```

Appendix C: Logistic regression code

```
#Vehicle type prediction

3) Code to make predictions about the type of vehicle


Road1 <- read.csv(file.choose(),header=TRUE)
head(Road1)

Road1W95 <- Road1[Road1$Season == "W" & Road1$Road == "US95",]

Road2id8 <- Road1[Road1$Season == "W" & Road1$Road == "ID8",]

# view the data
boxplot(Dec ~ Vtype, data=Road1W95, las=2, xlab="")
boxplot(Dec ~ Vtype, data=Road2id8, las=2, xlab="")

# this code separates the data into a training set and a test set
install.packages("dplyr")    # if not installed already
library(dplyr)
train <- sample_frac(Road1W95, 0.7)
sample.id <- as.numeric(rownames(train))
test  <- Road1W95[-sample.id,]

> dim(train)
[1] 75  6
> dim(test)
[1] 32  6

# declare one level for others to be compared to,
# this choice should not affect the results
train$Vtype <- relevel(as.factor(train$Vtype), ref = "P")

install.packages("nnet")   # if not installed already
library(nnet)

# fit multinomial logistic regression model
cartype.fit <- multinom(Vtype ~ Dec, data=train)

summary(cartype.fit)

# these lines examine predictive accuracy on the training data
head(probability.table <- fitted(cartype.fit))
train$predicted <- predict(cartype.fit, newdata=train, "class")
ctabletrain <- table(train$Vtype, train$predicted)
ctabletrain
round( sum(diag(ctabletrain)) / sum(ctabletrain)*100,2)
```

```
probs <- fitted(cartype.fit)
trainall <- cbind(train,probs)
(trainall)

newdata <- trainall[order(trainall$Dec),]
newdata


# only 49% accuracy

# these lines examine predictive accuracy on the test data
test$predicted <- predict(cartype.fit, newdata=test, "class")
ctabletest <- table(test$Vtype, test$predicted)
ctabletest
round(sum(diag(ctabletest))/sum(ctabletest)*100,2)
# only 34% accuracy, but the rows are in a different order


#Same process but for ID-8
Road2id8 <- Road1[Road1$Season == "W" & Road1$Road == "ID8",]
boxplot(Dec ~ Vtype, data=Road2id8, las=2, xlab="")

train2 <- sample_frac(Road2id8, 0.7)
sample.id <- as.numeric(rownames(train))
test  <- Road2id8[-sample.id,]
train2$Vtype <- relevel(as.factor(train2$Vtype), ref = "P")
cartype.fit2 <- multinom(Vtype ~ Dec, data=train2)
summary(cartype.fit2)

head(probability.table <- fitted(cartype.fit2))
train2$predicted <- predict(cartype.fit2, newdata=train2, "class")
ctabletrain2 <- table(train2$Vtype, train2$predicted)
ctabletrain2
round( sum(diag(ctabletrain)) / sum(ctabletrain)*100,2)

probs2 <- fitted(cartype.fit2)
trainall2 <- cbind(train2,probs2)
(trainall2)

newdata2 <- trainall2[order(trainall2$Dec),]
newdata2
newdata[,c("P"), drop=FALSE]
```

```
#Shown below is the summary of the multinomial logistic regression
model
> summary(cartype.fit)
Call:
multinom(formula = Vtype ~ Dec, data = train)

Coefficients:
    (Intercept)       Dec
O     -63.11217 0.7379495
PI    -27.20869 0.3339641
PWS   -25.61729 0.3105594

Std. Errors:
    (Intercept)       Dec
O     14.848486 0.1742873
PI     8.801471 0.1084615
PWS    9.211382 0.1133969

Residual Deviance: 159.4162
AIC: 171.4162
```

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