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Emergency Vehicle Siren Noise Effectiveness

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by

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ABSTRACT

Navigating safely through traffic, while responding to an emergency, is often a challenge for emergency responders. To help alert other motorists, these responders use emergency lights and/or sirens. However, the former is useful only if within clear visual range of the other drivers. This shortcoming puts a greater emphasis on the importance of the audible emergency siren, which has its own shortcomings. This study considered several emergency siren systems with the goal to determine the most effective siren system(s) based on several criteria. Multiple experimental measurements and subjective analysis using jury testing using an NVH driving simulator were performed. It was found that the traditional mechanical siren was the most effective audible warning device; however, with significantly reduced electrical power requirements, the low frequency Rumbler siren, in conjunction with a more conventional electronic Yelp siren, was the preferred option. Recommendations for future work are also given.

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NOMENCLATURE

λ	wavelength (m)
c	speed of sound (m/s)
AKA	also known as
B&K	Brüel and Kjær
dB	decibels
dBA	A-weighted decibels
DI_θ	directivity index (dB)
DIN	Deutsches Institut für Normung
EMVC	emergency medical vehicle collisions
EMS	emergency medical service
EVSN	emergency vehicle siren noise
f	frequency (Hz)
FFT	Fast Fourier Transform
ft	feet
FVS	Full Vehicle Simulator
f_2	frequency in the upper edge of the octave interval (Hz)
f_1	frequency in the lower edge of the octave interval (Hz)
h	hour
HATS	Hats and Torso Simulator
HVAC	Heating, Ventilating, and Air-Conditioning
Hz	Hertz (1 cycle per second)
km	kilometre
LN	loudness level
L_P	sound pressure level (dB)
L_W	sound power level (dB)
m	metre
n	the number of octaves
N	loudness (sone)
P	sound pressure (Pa)
P_0	reference sound pressure, $2x10^{-5}$ Pa
Pa	Pascal
PC	paired comparison
phon	unit of loudness level
r	distance from source to receiver (m)
s	second
SAE	Society of Automotive Engineers
SD	semantic differential
SPL	sound pressure level
sone	unit of loudness
W	sound power (W)
W	Watt
W_0	reference sound power, 10^{-12} W

CHAPTER 1

INTRODUCTION

As a due service to the public, the assurance of the continuous improvement of one's safety within society to enhance the quality of life is vital. Pertaining to emergency response services, the unambiguous purpose is the associated acts performed at the site of the emergency event in question. However, a typically overlooked and crucial component is the journey of these emergency responders. Whether it is police, fire and rescue, or medical response services, the responders are attempting to arrive at the destination as quickly and as safely as possible. In order to progress through traffic, these vehicles are equipped with warning systems to alert both nearby pedestrians and the drivers of nearby passenger vehicles. These warning systems are required to contain a minimum amount of both visual and audio warning cues [1].

With this information in mind, a desired need for future further analysis into this technology becomes of interest. Nevertheless, simply desiring expanded investigation does not warrant the need for a research project of this magnitude. The project was originally brought to the University of Windsor's attention by the City of Windsor Police Services after several tragic events occurred; within the course of a single calendar year, five vehicle collisions involving emergency vehicles were recorded, of which, one incident resulted in the fatality of a civilian. The City of Windsor is more than willing to spend the necessary funds on new or additional siren equipment and/or modifications, if such changes produced a demonstrable increase in the effectiveness of the siren systems. The given is that an enhanced effectiveness of the siren systems will ultimately lead to increased safety on the roads.

The visual warning signaling system is the primary tool for the detection of emergency vehicles and generally consists of a series of LED lights enclosed in different coloured lamps. Generally, the mounting location of these lights is on the roof of the vehicles where their 360° rotation provides further coverage to all relative areas. It is sometimes the case that these lights are set on strobe modes to increase the alerting capability. Additional lights are often present on the front bumper, sides, and even the rear area of the vehicle to enhance the effectiveness. The use of reflective paints on the emergency vehicles also aids in the effectiveness, particularly in nighttime conditions. Many different types of light bars, lamp colours, mounting locations, and light patterns exist that all appear to serve a specific function and each with its own set of advantages and disadvantages.

Unfortunately, the visual warning devices are virtually useless if the emergency vehicle is outside of the visible range of the receiver. As this poses a significant problem in urban traffic intersections, an audio warning system is necessary. This system is comprised of siren sounds designed to alert drivers and pedestrians before the emergency vehicle comes into sight, which in turn permits more time to take the proper course of action. The descriptive term for the sounds produced from these vehicles is Emergency Vehicle Siren Noise (EVSN).

Unlike the visual warning systems, the siren technology is very limited and the traditional view is that it is ineffective. The main reasoning behind this stance is that the siren is very difficult to hear inside the cabin of a vehicle at distances greater than 8-12 m [2]. The measured width of a standard multi-lane traffic intersection can be significantly greater than 12 m, which supports the limits of siren systems. In addition, the sounding of the siren occurs prior to the emergency vehicle reaching the intersection, and as a result, the source-to-receiver distance could easily be over 20 m. Apart from being extremely difficult to hear, the localisation of the sirens is also extremely low, particularly when attempting to determine if the emitting source is from the front or the rear of the receiver [3]. The generally held belief is that these limitations of the siren's effectiveness are due to both the type of siren system employed as well as the listening environment.

The layout of this thesis is as follows. Chapter 2 is a review of the pertinent literature from previous and related studies of EVSN. This includes discussions of related background material including the history of siren systems as well as a review of the fundamentals of acoustics. This is followed by an in-depth review of past research related to siren noise. Any identified shortcomings in the current state of art are identified for inclusion in this study. In addition, relevant information pertaining to the factors, which are believed to affect present siren systems, is included. Chapter 3 details the experimental approach for this study, including the experimental design and procedures for both the data acquisition and the subjective evaluations. The results of the experiments are provided and analysed in Chapter 4 followed by a discussion of the results in Chapter 5. Any identified limitations and uncertainties are also discussed in Chapter 5. Finally, the conclusions and recommendations of the research as well as suggestions for future work are provided in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

The following chapter is a review of the available literature pertaining to emergency vehicle siren noise (EVSN), with a specific focus given to the evaluation of measuring the effectiveness of EVSN. Also of interest are studies having any specific parameters, which may hinder the effectiveness of sirens or compare the effectiveness of different types of siren systems or specific sounds. These are important to support the goal of this thesis, which is to provide information relating to the effectiveness of different siren technologies and to make recommendations for improvements. While existing studies appear to have not investigated this goal to any depth, a review of the studies pertaining to ESVN is essential to the understanding of the research presented in this thesis.

Ample research is available that pertains to the study of various siren noise attributes for a variety of test scenarios [1]. The results of these investigations are important to this research as they provided knowledge and understanding of how sirens operate and how effective they are under certain operating conditions. These studies also provide insight into what areas of the science are lacking and require further investigation.

Literature pertaining to jury testing guidelines and procedures is also included as these concepts are fundamental to some of the conclusions developed by this research. Understanding this first requires a basic understanding of acoustics and its propagation, as well as how humans perceive these sounds.

2.1 Fundamentals of Acoustics

An understanding of the fundamentals of acoustics and the associated terminology is essential for both the literature pertaining to other siren studies as well as the results from this investigation.

2.1.1 Basic Terminology of Acoustics

Sound is a pressure fluctuation characterized as a wave motion propagating through air (or other elastic media) which results in the excitation of our hearing mechanism and ultimately gives us the perception of the sound [4]. In other words, the definition of sound can be said to have two components; the physical component which deals with the propagation of the acoustic energy, followed by the psychophysical component which deals with the interpretation of the sound, otherwise known as psychoacoustics. The physical study of sound is a problem of physics, such as the disturbance and propagation in air created by a loudspeaker. On the other hand, if the interest is how the perception of sound by a person occurs, psychophysical methods are required [5]. For the purposes of this study, both the physical and psychophysical metrics are studied.

In addition to the above, a third fundamental quantity requires definition; noise. Noise is any sound, which either disturbs the intended silence or the intentional observation of another sound. Either of these situations generally leads to annoyance [6]. However, noise does not always need to fall into this generalized category. While noise is usually undesirable, in some cases it may be a carrier of information [5]. The emergency siren is a prime example of the latter, where most people consider the sound as unpleasant but it serves the purpose of conveying important information. It is also worth noting that certain sounds may be unpleasant to some people, but not to others resulting in sounds being considered as ‘noise’ to only certain people [5]. This can be due to one’s previous experience or preference and is associated with the much more difficult subject of psychoacoustics discussed in more detail in a later section.

Aside from the overall level of sound, an important characteristic of sound is the frequency (f) of the propagating acoustic energy, which is a characteristic of the periodic sound wave. The relationship of frequency with the speed of sound in the medium (c), approximately 344 m/s in air, and the wavelength of the periodic wave (λ), as shown in Equation 1 is:

$$f = \frac{c}{\lambda} \tag{1}$$

The audible frequency range for the human ear is from 20 Hz to 20,000 Hz [5]. Knowing this range is important for the study, as siren noise is included in only a very small segment of this spectrum.

The most common unit of noise measurement is the decibel (dB) which is a logarithmic representation of the strength of a sound unit, relative to a specified reference level; the threshold of hearing [1]. Sound is most often quantified as either a sound pressure level or sound power level. Sound pressure level (SPL), often noted as L_p, is the acoustic sound pressure (P); expressed in decibels above the standard sound pressure (P_0). Sound pressure level is dependent on the environmental factors within the propagation path, including the distance between the source and a receiver. That is, the strength of the source at a receiver location diminishes as the distance between the source and receiver increases. Sound power level (L_W) is the acoustic sound power (W) expressed in decibels above a standard reference sound power (W_0). Sound power level (unit of decibel) is a characteristic of the source and is independent of environmental factors associated with the propagation path [5]. As such, sound power is the preferred descriptor of a sound source; however, it is difficult to quantify. The general formulae for the relationships between the sound pressure level and the sound power level are:

$$L_p = 20log_{10}\left(\frac{P}{P_0}\right) \tag{2}$$

$$L_W = 10log_{10}\left(\frac{W}{W_0}\right) \tag{3}$$

$$L_W = L_P + 20log_{10}(r) + 11[dB] - DI_\theta \tag{4}$$

$$L_{P_2} = L_{P_1} - 20log_{10}\left(\frac{r_2}{r_1}\right) \tag{5}$$

$$L_{P_{TOTAL}} = 10 * log\left[\sum_{i=1}^{N} 10^{\left(\frac{L_{P_N}}{10}\right)}\right] \tag{6}$$

Directivity Index (DI_θ) in the above Equation 4 is a correction factor used to account for nonlinear radiation of the source as well as environmental absorption and reflections in the propagation path. For example, the sound pressure level of an ideal spherically radiating point source will decrease by 6 dB for each doubling of distance [1]. It was also important to mention that, given the sound power of a source, Equation 4 predicts the sound pressure level at another point along a radial line originating at the source (Equation 5), if the distance (r) between the source to the receiver is known.

Also pertinent to this study is an understanding of how humans perceive changes in sound level. In general, a minimal change of 3 dB is necessary for the human auditory system to perceive a change in sound level. It should be understood that a change in the sound level is not proportional to a change in the perceived loudness of a sound. Presented in Table 1 are other perceived changes in sound level.

Table 1: Change in sound level relation to change in perceived loudness [4]

Change in Sound Level (dB)	Change in Perceived Loudness
1-3	Just perceptible
5	Noticeable difference
10	Twice (or 1/2) as loud
15	Large change
20	Four times (or 1/4) as loud

For the analysis of sound, the division of a signal into specific frequency bandwidths is useful with the most common being either octave or third octave band analysis. Octave presentation of a sound is a 2:1 ratio of two frequencies that represent the upper and lower limits of the band interval as given in Equation 7 below [5].

$$\frac{f_2}{f_1} = 2^n \tag{7}$$

It is more common for noise measurements to use third octave band analysis, as this bandwidth better represents the inherent filtering network of the human auditory system.

A final attribute of sound measurements that warrants discussion is frequency weighting. Humans do not hear sounds at all frequencies with the same ability. The ear's ability to perceive low and high frequency sounds is not as good as mid frequency sounds at approximately 1000 Hz. To account for this nonlinearity; a weighting scale adjusts the measured values of sounds to provide a better match to perception by the auditory system. The most common correction is the A-weighting curve and environmental noise measurements often use it, as is the case in this research. The A-weighting correction is also the basis of the psychoacoustic metric of loudness, which will be discussed later in this thesis.

2.1.2 Psychoacoustic Terminology

The study of the structure and mechanics of the ear falls under the study of its physiology. Alternatively, the study of how the auditory system perceives sound falls within the study area of psychology. From these, the term psychoacoustics provides an inclusive term embracing the physical structure of the ear, the sound pathways, the perception of sound, and their interrelationships. Psychoacoustics is pertinent to this study as it emphasizes both structure and function of the human ear [5].

It is known that noise can cause stress in people and that the onset of loud noise can produce effects such as fear and significant changes in pulse rate, respiration rate, blood pressure, metabolism, acuity of vision, skin electrical resistance, etc. [7]. Although the side effects of noise are not the focus of this study, they are valuable to note as these changes can have an impact on a driver or a pedestrian who is exposed to excessive levels of sound.

Measurements of a siren's sound pressure level and sound power level are essential for understanding the physics and engineering of sirens as well as quantifying their noise characteristics. However, the data from these measurements is not sufficient to meet the goal of this project, which is to determine the effectiveness of EVSN. In order to fulfill the requirements of this project, it was essential that this research focused on both the physical and psychoacoustic components of siren noise.

2.1.2.1 Loudness

While many psychoacoustic quantities are significant to acoustics, a major metric used in this study was loudness. Loudness is a psychoacoustic term used to describe the magnitude of an auditory sensation. Although it is common to use the terms "very loud," "loud," "soft", etc. which correspond to musical notations, it is evident that these terms are not scientifically valid. This is because these terms have no numerical value, as they are subject to the expression of a person's perception and experience. The fact that these terms are perception based is the major reason why using the label of loudness is flawed as no two person's perception of sounds is identical [8]. A simple example of this difference in perception is that of a fingerprint, in the sense that although the fingerprints of two people may be very similar, and may appear the same, they are not in fact identical.

For certain sounds, there can be multiple aspects to the loudness impression. In other words, the listener may judge different 'types' of loudness. In speech for example, a listener may judge short-term loudness (the loudness of a specific syllable) or another listener may judge overall loudness of a relatively long segment (the loudness of the overall sentence) [9].

As with sound pressure and sound pressure level, there are separate definitions for loudness and loudness level. Using equal level contours, the loudness level of a sound is equal to the sound pressure level of a 1000 Hz sinusoid that is judged equally as loud. This 1000 Hz sinusoid is presented in a free field domain with frontal incidence and the listener experiences it with both ears. The unit of loudness level is the phon. It is also important to note that the investigator must record the manner of listening to the unknown sound. The definition of loudness, on the other hand, is a numerical designation of the strength (with a unit of sone) of a sound. It is proportional to the subjective magnitude as estimated by listeners who have 'normal' hearing. The relationship between frequency, sound pressure level, and loudness is shown in Figure 1.

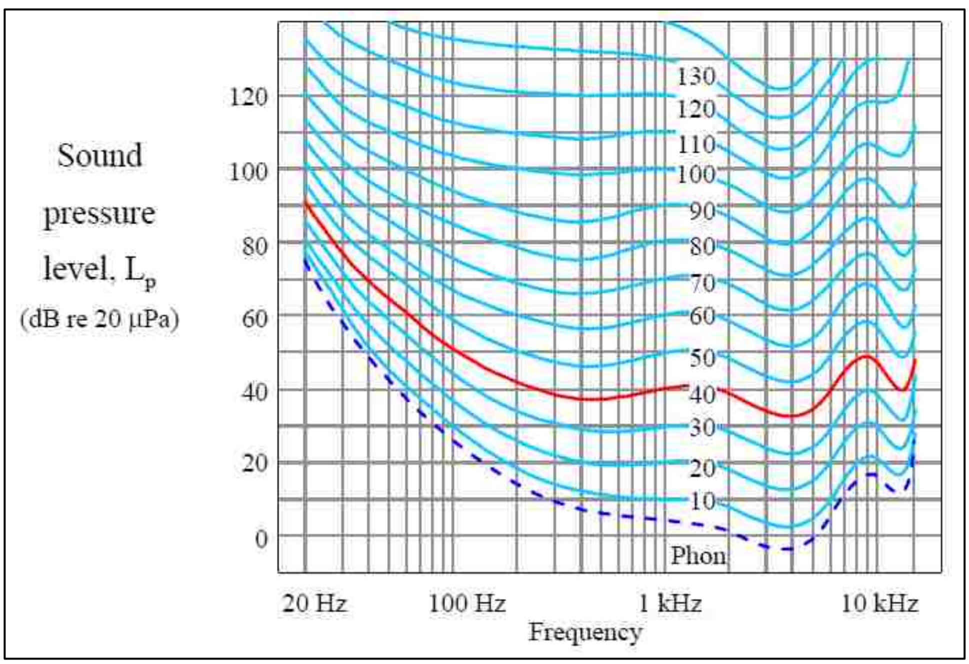

Figure 1: Equal Loudness Contours [4]

As stated previously, a relationship exists between sound pressure level and loudness level. The definition of one sone is the loudness value of a 1 kHz tone having a sound pressure level of 40 dB relative to the reference value of 20 μPa. Above this value, an increase in 10 dB is equivalent to a doubling of the perceived loudness; 20 dB represents a sound four times as loud, and so forth. This relationship compliments the relationship depicted in Table 1. The relationship between sones and phons is that one sone is equivalent to a loudness level of 40 phons, and an increase in 10 phons results in doubling of the loudness [10]. Presented in Equation 8 is the relationship between loudness (N) and loudness level (LN) [11].

$$\mathrm{N} = 2^{\left(\frac{\mathrm{LN}-40}{10}\right)} \tag{8}$$

It is important to note that this is a simple representation of a more complex equation. In addition to providing the relation between sound pressure level and loudness level as shown in Figure 1, Equation 8 also connects with the fact that the sound pressure level in decibels (again at a 1 kHz tone) is equivalent to the loudness level in phons.

Two loudness standards are currently in use today. For the purposes of this project, the in-depth history and background of these models are not relevant. The Zwicker Method was the first loudness model to be standardized and was originally capable of determining loudness for stationary sounds only [12]. These models have since been updated, to have better correlation to human perception and to accommodate time-varying sounds including the DIN 45631/A1 method [11]. The other method is the Glasberg and Moore Method, which is growing in popularity. As with the Zwicker Method, the original Glasberg and Moore standard was not capable of computing unsteady-state sounds. A recent update to this model has overcome this limitation.

Another interesting feature of this model is its ability to analyze thresholds for time-varying sounds in the presence of background noise [9].

2.1.2.2 Other Psychoacoustic Characteristics

While loudness is the most significant psychoacoustic characteristic, there are other factors that play important roles in this research. The first is sharpness, which can most easily be described as a measure of the tone colour of a sound. Adding sharpness to a sound gives it a character of powerfulness, however, too much sharpness and the sound will be perceived as aggressive. Sharpness can be easily estimated through calculation if the loudness pattern of the sound is available. Roughness is governed by temporal variations of a sound and reaches a maximum for modulation frequencies around 70 Hz. In essence, roughness can be described by the temporal-masking pattern of sounds. Another characteristic is fluctuation strength, which is similar to roughness but it reaches a maximum at modulation frequencies of approximately 4 Hz. The final quantity is composed metrics, which is a combination of psychoacoustic quantities that have proven successful for the prediction of annoyance of sounds [13].

2.2 Siren and Associated Attributes

This study does not focus on a specific sound characteristic, or a particular device for that matter, and thus it is necessary to introduce the technology of the siren and its components and related attributes.

2.2.1 History of the Siren

During the 1790's, the first siren was invented by physicist John Robison. This siren was developed for the sole purpose to be used as a musical instrument; specifically, it powered the pipes in an organ [14]. It was not until 1819 that Charles Cagniard de la

Tour invented an improved siren. It was still of the mechanical ‘family’ and was powerful enough to produce sound underwater. This technology employed perforated disks; one of which would rotate and the corresponding interruption to the fixed disk would produce a tone [15]. During this period, sirens were used as signaling devices, but only for trains and inside factories and not yet for emergency response purposes.

In 1886, George Slight developed a device that was considered a major overhaul to the technology of sirens and is still used today [16]. Instead of disks, this new design uses two concentric cylinders, which have slots parallel to their length; only the inner cylinder rotates and as air pressure flows out of the slots of the outer cylinder, the periodic interruption of the flow creates a tone. Once electric power became readily available, sirens were no longer driven by external sources of compressed air. It was not until the early years of the 20th century that sirens would be commonly used as warning devices. The next stage in siren advancement was the mounting of these devices on emergency vehicles, which did not occur until the late 19th century with the introduction of automobiles. Soon after, emergency vehicles incorporated the use of sirens.

2.2.2 Basic Siren Characteristics and Requirements

A siren in terms of its appliance to EVSN is defined as an audible warning signal that must meet the following requirements: [17]

A siren as a warning device must:

1. Be easily perceived in any noisy conditions.
2. Be easily perceived in every age group, including elderly with hearing loss.
3. Be easily recognizable as a warning signal even after being perceived.

4. Have universality transcending national boundaries; in other words, the signal must be recognized as an emergency warning in any country or language.

Recommended attributes to aid in meeting the mentioned criteria include: sufficient power and wide frequency spectrum to overcome masking noise, rapid rise of pitch, and relatively rapid cycling time (period required for the siren to sweep from the lowest to the highest fundamental frequency and back to the lowest [18]) [19]. The siren and the lighting systems work together to maximize early detection, recognition, and response to an oncoming emergency vehicle. Sirens generally provide the earliest detection, especially in urban environments where it can be difficult to become aware of the emergency vehicle. The lighting system provides improved ability to locate the vehicle so that a proper response occurs [1]. Currently, the general belief is that sirens are limited in their function as a warning device and no siren fulfills all of the requirements presented in the list above. The observation in many studies is that compromises of certain siren attributes must happen [20]. There is no assurance that all motorists and pedestrians will always hear, recognize, or react promptly in all typical circumstances [18]. However, a common question arises: “Why isn’t the amplitude of the siren increased to solve the perceiving issues?” Typically, this is a practical solution to many acoustical problems, particularly in everyday life. For example, if you are watching television and the background noise is high, you solve the problem by adjusting the volume on the television. Unfortunately, this rationale cannot be applied to sirens, as the sound produced exceeds the limit of damage risk and is approaching the pain threshold for human hearing. Figure 2 provides an illustration to explain this phenomenon further.

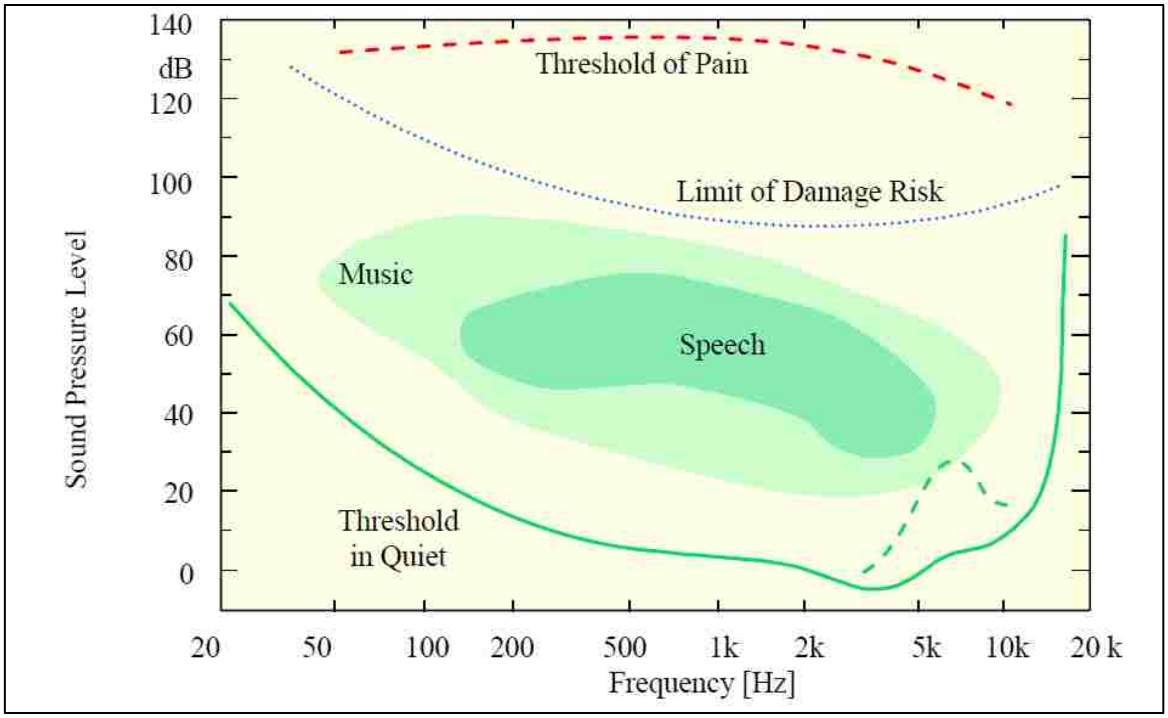

Figure 2: Human perception of sound [4]

As seen in Figure 2, the Limit of Damage Risk curve is dependent on the frequency and has a minimum value of approximately 90 dB. Certain sirens used in North America produce a sound power level up to 119 dB [1]. Fortunately, that value is just under the Threshold of Pain curve, which has a minimum value of 120 dB. Past studies have linked hearing loss to repeated siren exposure of emergency medical service personnel [19]. Given that the majority of modern emergency vehicles employ similar siren systems, this finding can also be said true for police and fire and rescue services personnel. This point was the core factor pertaining to the reason siren devices could not simply be adjusted to emit a higher sound level.

2.2.3 Siren Types

To expand upon the previously stated definition, a siren is a device or system that produces acoustical signals that continuously vary in frequency and call for the right-of-way of an emergency vehicle. These signals (and the electrical signals that are responsible for producing them) are generally referred to as siren signals [18]. With this definition, it is important to note that sirens are generally classified as either electronic (AKA electrical) or electromechanical (AKA mechanical) siren systems. An electrical siren system is composed of two main components; the first is an electronic siren amplifier, which is a device powered by the electrical system of the vehicle and produces an electrical signal that drives an electronic siren speaker, which is the second component. An electronic siren speaker is comprised of a transducer that converts the electrical signal produced by the electronic siren amplifier into acoustical energy. On the other hand, a mechanical siren system is a device that converts electrical energy directly into acoustical energy without the aid of an electronic power amplifier [18]. Currently, many emergency vehicles equipped with mechanical sirens are being outfitted with electrical siren systems. Another important characteristic of the mechanical and electrical sirens is the corresponding sound waves they produce. The mechanical system produces a waveform that approximates a square wave, while the electrical system produces the traditional sine wave. Figure 3 provides a basic illustration of these waves for different sound levels [17].

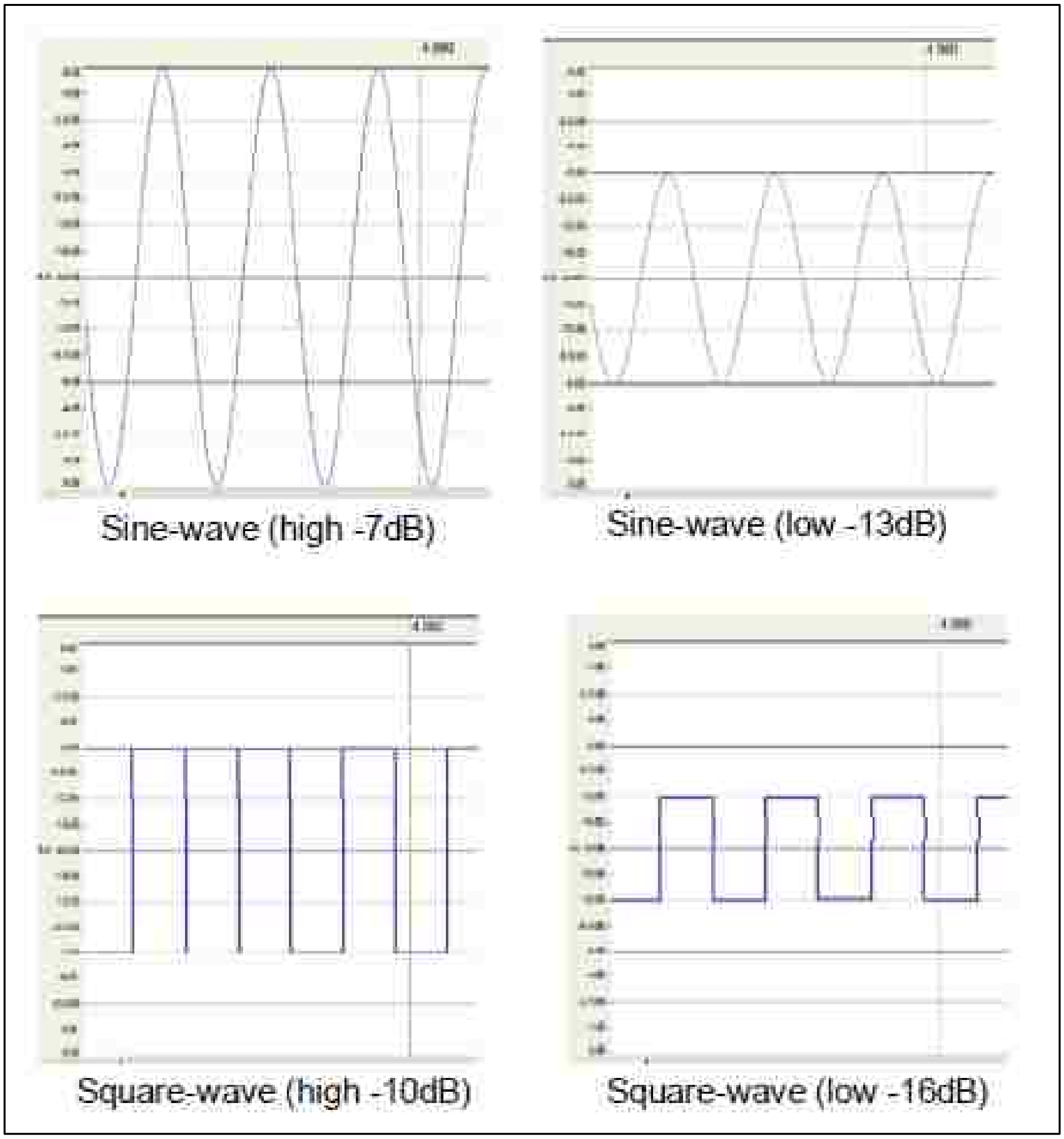

Figure 3: The sine wave and the square wave

Within the last decade, a new type of siren system has been introduced into the industry, which emits a low frequency sound as opposed to the typical high frequency sound signal. This device provides a duplicate tone emitted by the standard electrical siren but in a lower frequency. It was important to note that this system is not a stand-alone device, as it 'compliments' the siren signal. Federal Signal, a technological leader in audible warning and operator safety, has developed their version of the system, which they have appropriately named “The Rumbler: Intersection-clearing System”. The siren technology produces a penetrating/vibrating low frequency sound wave that has the distinct advantage of penetrating solid materials, such as passenger vehicles, allowing vehicle operators and nearby pedestrians to ‘feel’ the warning signals. The Rumbler is believed to be highly effective in dense urban environments with heavy vehicle traffic [21], where typical siren systems emitting high frequencies have revealed significant problems [19].

2.2.4 Siren Modes

Traditionally, siren modes are categorized as either a Wail or Yelp signal. These are simply different modes of the siren operation, which produce the corresponding warning signal [18]. The air horn is another siren feature that works simultaneously with the regular siren system. This mode is often used by emergency medical response services and fire and rescue services when approaching an intersection [19]. As mentioned in the previous section, the low frequency siren system is capable of being incorporated with the existing siren modes for increased effectiveness.

2.3 Testing Guidelines

2.3.1 Field Measurements

As with any study in acoustics, there are certain procedures and guidelines to which the study should adhere. Prior to any experimental design and testing, the Society of Automotive Engineers (SAE) published report outlining the procedures for siren testing was reviewed. Typically, for vehicle siren system noise, the receiver is located at a distance of approximately 3 m from the source [1]. However, this is not a mandatory factor, as it depends on the type of measurement and goal of the study. For example, in comparing different mounting locations of the siren systems, a distance of 3 m is appropriate to carry out your measurements. However, if the study was to determine the effects of barriers on the effectiveness of sirens, a source-to-receiver distance of 3 m is not appropriate, as it is too short.

2.3.2 Jury Testing

As was the case with field measurement guidelines, the SAE had published work regarding guidelines for jury evaluations of automotive sounds. Again, this document was viewed as a reference containing 'rules-of-thumb' [22].

2.3.2.1 Listening Environment

There are controllable factors of the listening environment that affect subjective testing. The acoustics of the room, décor, ambient noise, and temperature play a significant role in obtaining an adequate listening space.

2.3.2.2 Subjects

The term, subject, refers to any person that takes part in the evaluation of sounds in a listening study. Subject selection is vital to any study as it encompasses subject type, number of subjects, and recruiting subjects (if applicable). Subject training may be required depending on the level of complexity of the tasks expected of the subject.

2.3.2.3 Sample Preparation

A good sample preparation practice pertains to the appropriateness of the sound samples used in a jury evaluation. This extends to the editing of the sound data as well as issues faced with data collection, which are included in the SAE document.

2.3.2.4 Test Preparation and Delivery

The first aspect of the test is the presentation of the samples to the subject. This includes pacing or timing, sample size, and sound reproduction method, which includes either loudspeakers or headphones. The second area is presentation (play) order. Much focus is placed on incorporating an appropriate method of controlling the sound presentation order to reduce experimental error due to biases as much as possible. For example, with a large number of sounds, the test can become undesirably long and to prevent this one should select only certain paired combinations for testing. Another similar task is the scaling task, where the subjects rate the sounds based on a set of criteria. The next aspect is the data collection environment. The most popular strategies include: forms processing, using software and a scanner (the “bubble-in” type of survey is among the most popular), a computer display which uses a desktop computer to administer listening tests, and hand held devices such as controller or PDA’s which could be setup to collect data into a computer for processing. The final component of preparation and delivery is the careful conveyance of any special instructions required by the subjects in order to obtain good data without inadvertently biasing the jury.

2.3.2.5 Jury Evaluation Methods

This section of jury testing is perhaps the most important as the methods of evaluation chosen can have a significant direct effect on the results of the study. The first method outlined is rank order, where the juror must rank a set number of sounds based on the established criteria. For simplicity, the number of sounds should be kept to six or lower. The major issue of this method is that it yields no scaling information.

The second method is the response (rating) scales method where the subject records their evaluation of the specified criteria of the sound on a scale, usually limited to a number between 1 and 10. While this method does solve the scaling dilemma mentioned in rank order, rating scales have their own list of issues for untrained/inexperienced subjects. The first is that the scale does not allow the subject to express their answer in a natural way. The listener generally has no idea what an "8" or "3" correspond to on the scale. The second problem is that different subjects use the scales differently. Some may only use a small range for a test while others may make use of the majority of the available scale. Another drawback of this type of test is that the subjects rarely use the extremes as they are 'saving' them in case the following sound is closer to the extreme. The final issue is that there is little reason to believe that ratings on an arbitrary scale should correlate with the objective characteristics of the sounds used in the test.

The next major method of testing is paired comparison (PC) testing. By definition, PC methods are those in which sounds are presented in pairs and the subjects are asked to make a judgment decision on the sounds in the pair. There are multiple types of PC methods used in jury testing; the first of which is detection tasks, where the subject must select which of the sounds in the pair contains the signal to be detected. Evaluation tasks, the second type of PC that asks the subjects to make relative judgments (pick A or B) of the presented sounds based on the evaluation criteria. Often evaluation tasks are repeated until all possible sound pair combinations have been evaluated; sometimes certain pairs will be removed from the test to avoid tests of long duration. The final type of PC method is similarity tasks, where the juror must make an estimated judgment on the sounds similarity.

The semantic differential (SD) technique allows the evaluation of multiple attributes of sound such as preference, similarity, annoyance, etc. This method offers the ability for the juror to evaluate multiple criteria, which is not possible with PC. The subjects evaluate sounds on a number of descriptive response scales, using bipolar adjective pairs, such as quiet/loud and smooth/rough. These are the two extremes for a given scale, with intermediate points available for selection between those extremes. Figure 4 illustrates a typical example of a seven-point scale for a quiet/loud category.

Figure 4: Seven-point scale for semantic differential evaluations [22]

Magnitude estimation is the final evaluation method. In applying this technique, subjects assign a number to some attribute of the sound (how loud or how pleasant it is). Generally, there is no limit or boundary to the range of numbers a subject can use, thus essentially making magnitude estimation a scaling task without the respective boundaries. A major disadvantage of magnitude estimation is that different subjects may give widely different magnitude estimates. One strategy to address the issue of subject variability is to present a reference sound with a specific magnitude (i.e. 50) and have all other sounds in the test rated relative to that reference; this is referred to as ratio estimation.

2.3.2.3 Analysis Methods

The intent of this section is to outline the data analysis of the methods discussed in the previous section. Magnitude estimation, rating, and semantic differential scales all fall into the category called interval scale, which contains all the information of an ordinal scale but also allows the computation of differences between sounds. As mentioned, magnitude estimation involves the subjects creating their own scales; there is a need to apply a method of normalization of responses prior to any statistical analysis. The distribution analysis of these three methods involve typical areas of interest, such as mean, median, mode, range, measure of shape, skewness, and kurtosis. Graphical techniques for analysis include scatter plots, normal probability plots, and histograms to name a few. Confidence intervals as well as testing and comparing sample means (t-test) are also useful analysis tools when examining data. Regression analysis (typically linear) is a technique used to assess the relationship between one dependent variable and one or more independent variables. Another statistical technique that is a useful tool is factor analysis. In application to the set of variables, it permits the discovery of which members of the set form coherent subsets that are relatively independent of one another. In other words, factor analysis reduces a large set of variables into a smaller set of variables, otherwise known as factors. There are two main types of factor analysis, each with their own set of complex and lengthy procedure.

Prior to examining PC data, it is important to note that while there are multiple methods, PC techniques are separable into two categories, forced choice and similarity. Forced choice tasks present the juror with two sounds, and yields one preferred choice based on the criteria. Certain factors play pivotal roles in this type. The first is the test of subject performance, which reveals how each subject individually, as well as the entire population, performs. Subject repeatability is a measure of the percentage of all comparisons judged the same for the first and second exposures in the test. It is important to note that the subject repeatability should be at least 70%, values below that may have their data removed [22]. If the average of the population is below 70%, then it is likely a problem exists within the test. Subject consistency is a measure of how well the pair judgments map into higher order constructs. Based on triads, the Kendall Consistency illustrates this factor. If A>B and B>C then it logically follows that A>C and is inconsistent if A<C. The final part of analysis for forced choice is the calculation of scores, which in turn obtains the rank order. The score for a given sound is simply the total number of times that sound is chosen summed over the total number of paired comparisons. For PC of similarity, performance measures for this type typically include histograms of subjects' numerical ratings to insure full use of the entire scale and the rating differences between replicate judgments. Analysis of similarity evaluations involves using non-metric multi-dimensional scaling, which is closely related to factor analysis [22].

Rank order data falls into the category of ordinal scaling and thus is subject to non-parametric statistical analysis. As discussed, values obtained from rank order evaluations indicate relative positions of sounds but not the magnitude of the differences between them. Significance and correlation tests are the two methods for analyzing the data obtained [22].

2.4 Previous Studies

As mentioned, a significant quantity of research is available in relation to EVSN; however, a proper understanding of the theory and testing background is required to analyze the past studies.

2.4.1 Auditory System

One aspect that is of significant importance to this study was examining how the auditory system copes with receiving and analyzing such a vast range of sound intensities. Isabel Dean investigated the phenomenon of how humans are able to listen to sounds that vary greatly in loudness. In comparing the threshold of human hearing at 0 dB to the upper limit of 120 dB, which correlates to one billion-fold higher in intensity, the human brain is accomplishing a remarkable feat [23]. This research is particularly relative to this study as siren noise correlates to a significant change in loudness compared to typical traffic noise.

It was described by Dean that one way in which auditory neurons respond to sound is by changing the electrical activity level; quiet sounds produce little electrical activity, or more accurately, a low rate of ‘firing’ of the electrical events, while loud sounds are the opposite. In the past, the belief was that the range of sound intensities that produce an increase in the neuronal firing rates seemed too narrow to cover the ranges of sound intensities experienced in everyday life. Also understood was that the maximum point of firing was typically reached by sounds that are only as loud as a normal conversation. The question Dean addressed was how neurons manage to code shouting voices or sirens for that matter. The conclusion of the research was that neurons could alter the range of intensities to which they respond. Furthermore, these alterations occur strictly based on the range of intensities that are present in the current listening environment. The adaption process was also determined to be extremely rapid, occurring over the course of hundreds of milliseconds [23]. This information was vital to this study as these adapting times may play a significant part in the reaction time of drivers and pedestrians.

2.4.2 Physical – Shadowing due to Vehicles/Barriers on Road

There are three categories of acoustic materials: absorbing materials, barrier materials, and damping materials [24]. Acoustic barriers placed in the path of a free field sound radiation will block part of the sound energy to the receiver and as a result create a relatively quiet zone in the acoustic shadow [25]. Three parameters control the level of acoustical attenuation by a barrier: the distance of the barrier from the source and the receiver, the wavelength of the sound, and the sound transmission loss of the barrier [26]. The size and form of the barrier are other important attributes that affect the attenuation [25].

For the study examined [2], two types of barriers were relevant to EVSN effectiveness: vehicles and barrier walls, the latter of which can be median dividers on the road as well as nearby buildings. The study confirmed that both walls and vehicles could act as barriers in relation to siren noise, resulting in reduced sound pressure levels in the shadowed area. The study confirmed that frequencies below 1000 Hz were more likely to refract around barriers as opposed to being absorbed [2].

A more recent study investigated the diminished effectiveness of an electrical siren system due to the effects of the shadowing vehicle. The study examined several different traffic scenarios and concluded that the presence of a blocking vehicle resulted in a significant change (decrease of approximately 5 dB) in the sound pressure level at the receptor [27].

2.4.3 Physical – Directivity

Directivity measurements are fundamental to acoustics as no real sound produces a radial emission. One study examined a siren loudspeaker that was tested in an anechoic chamber, in which case white noise was played through the loudspeaker. Figure 5 provides the results of the experiment. The measurements were taken at a distance of 1.8 m from the source and 0° refers to the line perpendicular to and centred on the front of the speaker.

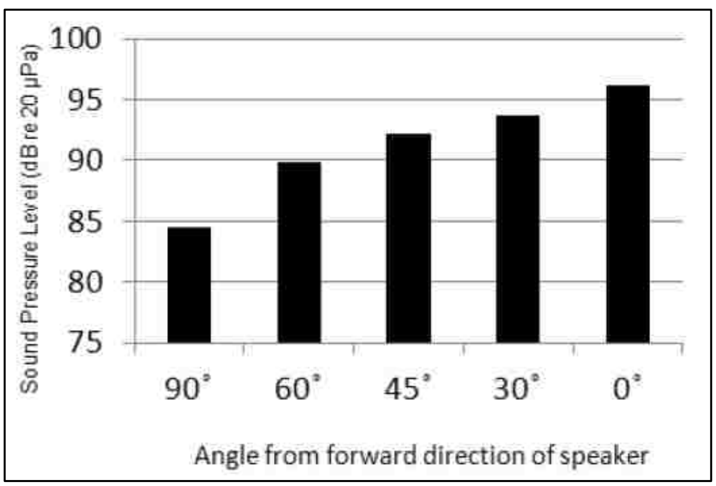

Figure 5: Total SPL for respective directions [2]

This data indicated an 11 dB reduction in SPL between the on-axis and perpendicular directions, which would be perceived as less than half as loud. This study recommended that a second pair of speakers be installed in emergency vehicles, directed sideways and activated when approaching intersections to combat the reduction in SPL [2].

As just discussed in the previous study [2], the addition of speakers facing perpendicular to the direction of the emergency vehicle was recommended; however, it is not as straightforward as simply installing another speaker system. When employing multiple speakers, it is crucial to ensure that both of the speakers are operating in-phase. In other words, both speakers must be emitting the same signal simultaneously. If this is the case, the speakers combine to produce a higher output, which is referred to as constructive interference. However, if the speakers are operating out of phase with one another, phase cancelation occurs, which results in a reduced sound output. An experiment involved the installation of a second speaker onto the inside grill of a police cruiser (both speakers facing forward) and testing of its directional sound output in comparison to the single speaker. Figure 6 displays the results of the experiment in a polar plot [1].

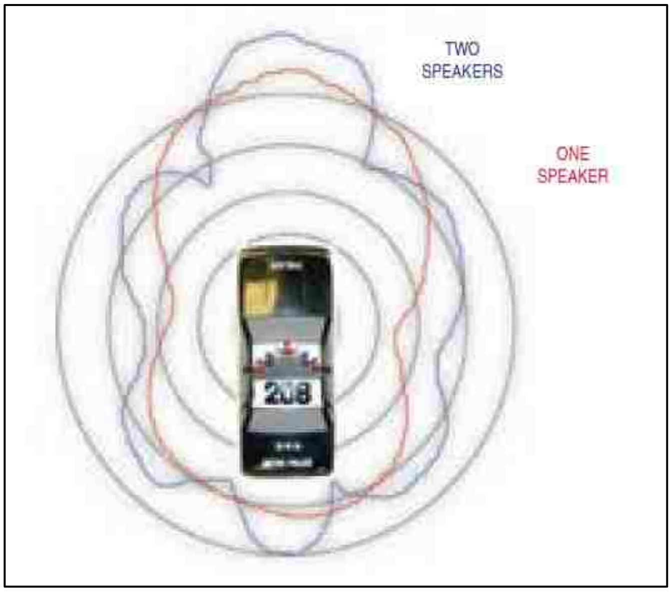

Figure 6: Polar plot measure of sound output of single and dual speaker system [1]

Several key points are evident from this data. First, the two-speaker siren system had increased sound energy in the frontal area of the vehicle, but areas of 'lobbing' are present, particularly toward the 45° points. Second, although the single siren speaker did not produce as high of a sound output as the two-speaker system, the lobbing effect was not present. In fact, the single speaker system outperformed the two-speaker configuration at +45° and −45°. This deficit of the two-speaker system was likely due to the speakers being spaced improperly from one another [1].

2.4.4 Physical – Noise Reduction of a Passenger Vehicle

An experiment was carried out to determine the noise reduction of a passenger vehicle. In other words, what effect does a vehicle itself have on the sound pressure level that the driver experiences. SPLs were recorded at the driver's position, for three speaker locations outside of the vehicle (front, rear, and driver's door of the vehicle) with the vehicle present. The test was repeated with the vehicle absent and was subtracted from the first set of data gathered. For this experiment, typical siren modes as well as the Rumbler siren were tested against one another and the results are shown in Figure 7 [20].

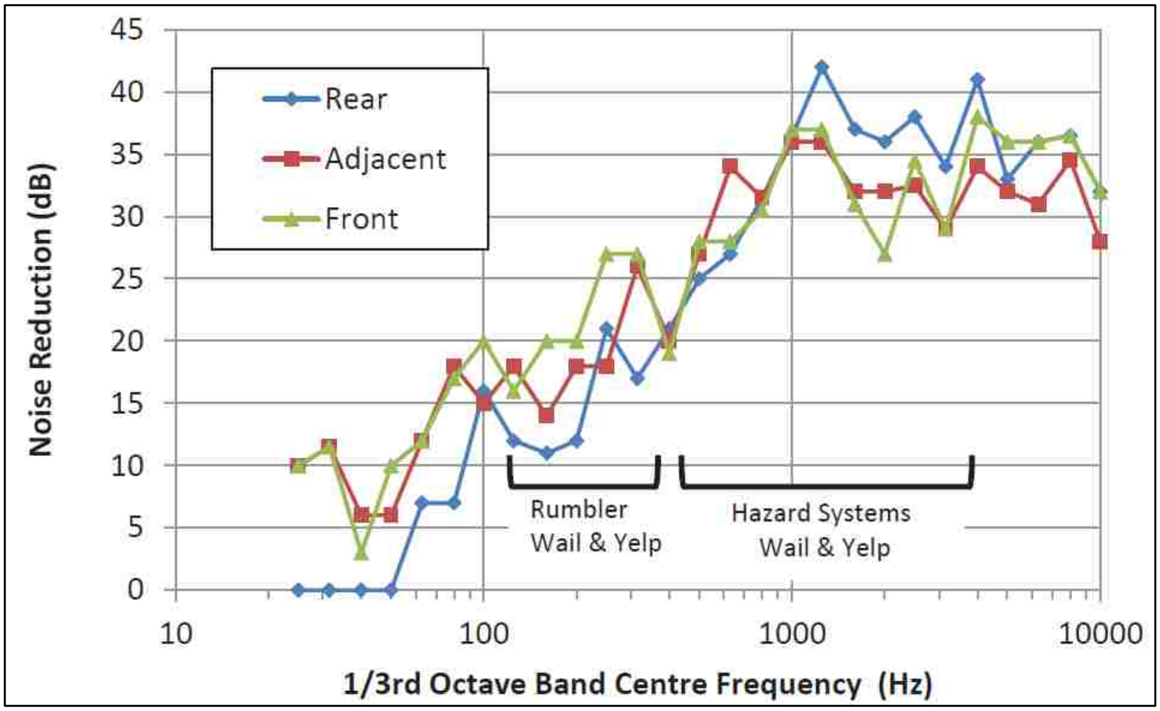

Figure 7: Noise reduction of a passenger vehicle [20]

As discussed previously, the Rumbler exhibited increased vehicle penetration capabilities due to its low frequency output, as shown in Figure 7. The conclusion from this study was that while all sirens were subject to noise reduction of a passenger vehicle, low frequency siren systems show a significant decrease in this reduction [20].

2.4.5 Physical – Attenuation Due to Distance

Presented earlier in this review, was the observation that SPL varies with distance. However, taking measurements at several distances can become time consuming, but sound power level measurements are independent of distance. A thorough study was undertaken where the sound power levels of 20 siren combinations were measured. Figure's 8 and 9 present the results of this study [20].

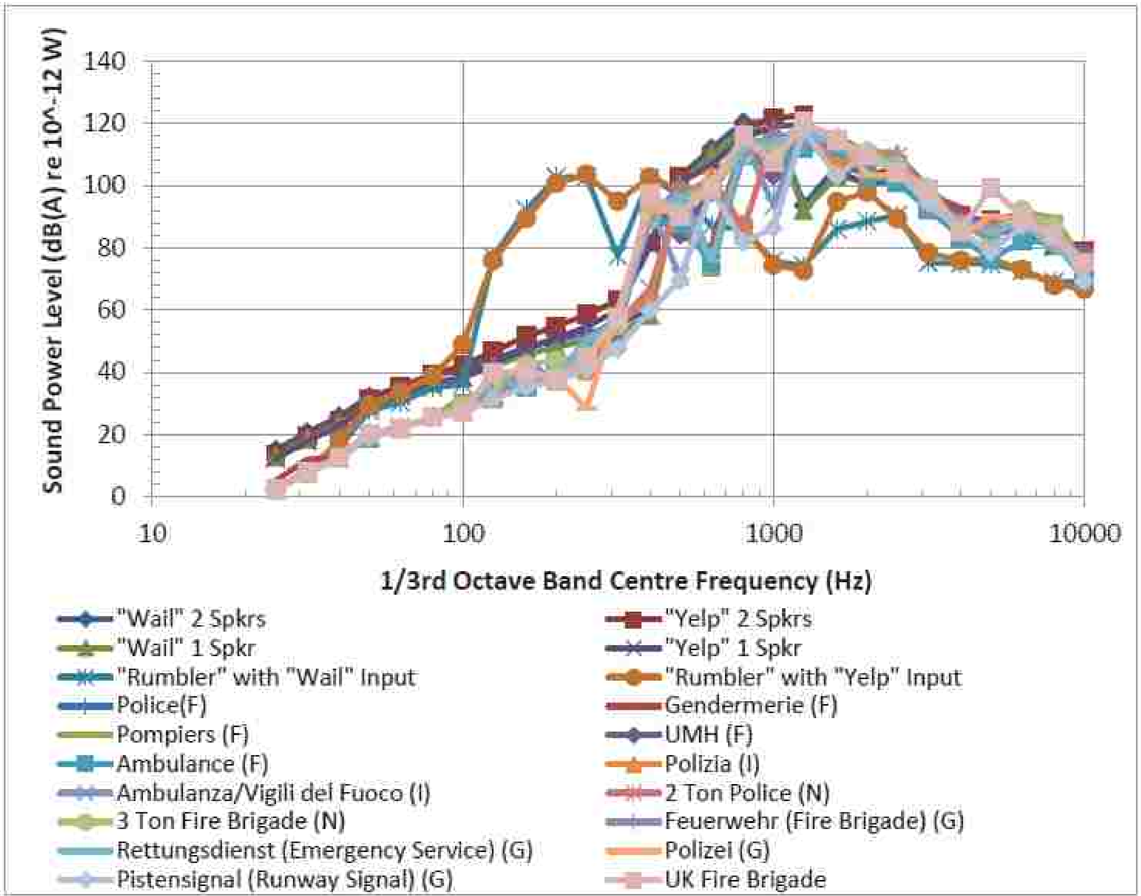

Figure 8: Sound power levels (A-weighted) [20]

From these results, it was observed that in both cases of the Rumbler system addition, higher sound power levels in the low frequency range were observed, primarily between 100 to 400 Hz. As the frequency increased beyond this point, the Rumbler became ineffective. For the overall frequency range, the Yelp two-speaker siren system performed the best. It is also important to note that for the most part, all of the other siren systems are practically the same, as a fluctuation of only a few decibels occurred [20].

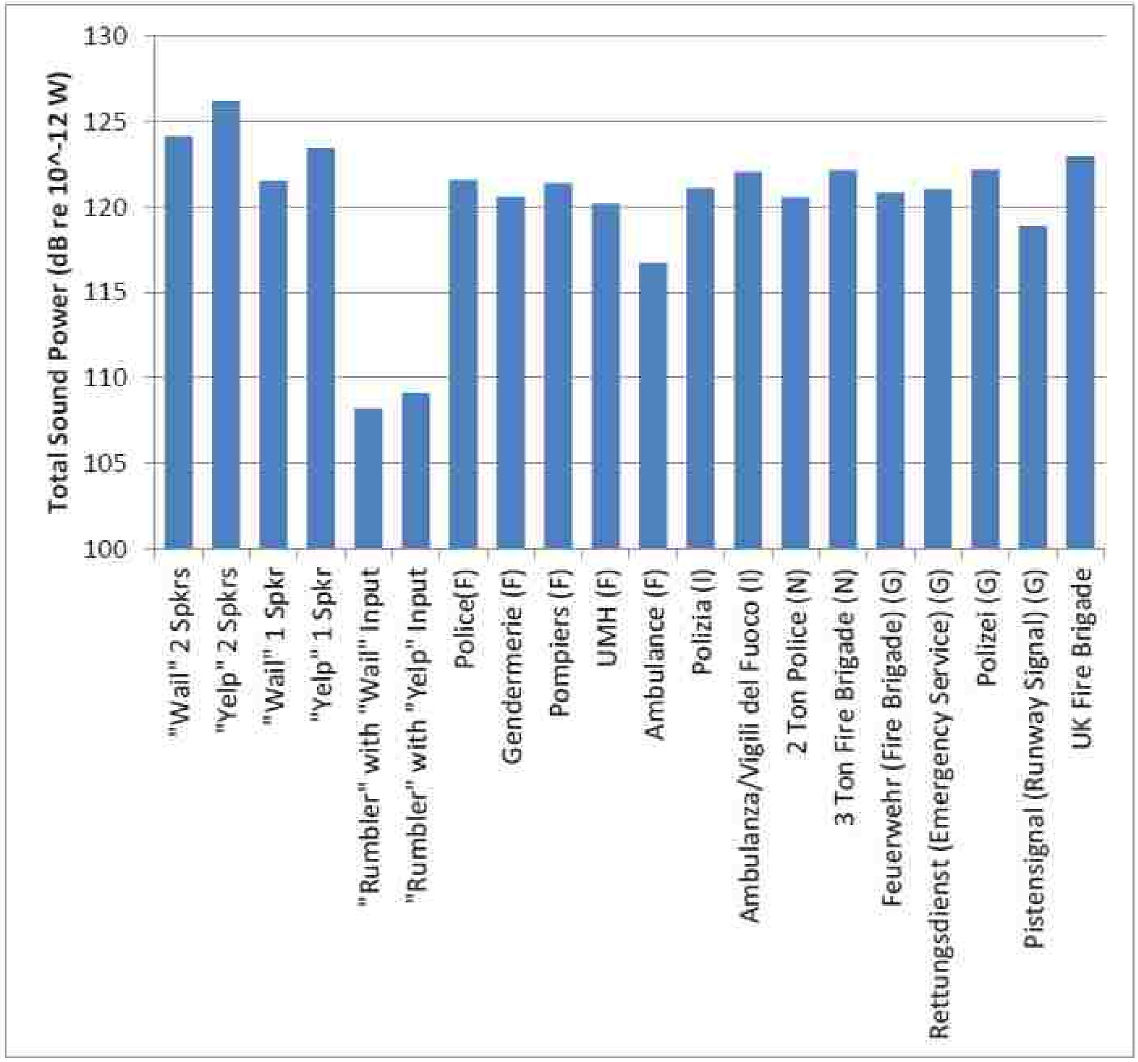

Figure 9: Total (A-weighted) sound power levels [20]

From Figure 9, both of the Rumbler addition inputs revealed a significantly lower maximum sound power output in comparison to all of the other siren systems. However, the results do not indicate that the Rumbler was an ineffective siren as it had higher vehicle penetrating ability, which can lead to a higher sound level within the cabin [20].

2.4.6 Physical – Effects of Back Pressure on Siren Loudspeaker

As emergency vehicles are typically travelling at high speeds (50-80 km/h) when the siren system is active, there is a potential for a reduction in the sound radiated from the siren due to the backpressure acting upon the loudspeaker diaphragm. SPL tests were carried out which placed the siren both outside and inside a wind tunnel at the speeds mentioned. A comparison of the measurements against one another indicated that the measurements from the wind tunnel tests manifested no degradation. Upon this finding, the siren loudspeaker was dismantled and it was determined that the speaker contained a pressure compensating design with ports connected to the front and rear of the speaker. Thus, the sound of the siren device was self-compensating for wind loading effects [2].

2.4.7 Psychoacoustic – Perceived Urgency

Perceived urgency is a factor that is dependent on the characteristics of the sound. It is defined as the degree of urgency that a listener judges a sound to have. It is a significant factor pertaining to subject reaction times. It has been determined that the repetition period, also known as the cycling time of the signal, had the greatest influence on perceived urgency. To simply state, a rapidly repeating signal is perceived to be more urgent than a slowly repeating signal. Perceived urgency is an important characteristic for hazardous situations, such as intersections where a quick response time is crucial. A series of siren repetition periods were recorded and Table 2 presents the results. From the data, it is evident that the MS4000 Priority had the shortest repetition period of 0.05 s, which was more than 80 times shorter than the Wail siren mode [2].

Table 2: Cycling time of siren signals [2]

Siren Signals	Period (s)
Wail	4.11
Yelp	0.35
MS4000 Priority	0.05
MS4000 Scan 1	0.09
MS4000 Scan 2	0.23
Police (F)	1.11
Gendarmerie (F)	1.12
Pompiers (F)	2.25
UMH (F)	1.12
Ambulance (F)	2.04
Polizia (I)	1.53
Ambulanza/Vigili del Fuoco (I)	1.51
2 Ton Police (N)	1.52
3 Ton Fire Brigade (N)	3.05
Feuerwehr (Fire Brigade, G)	4.08
Rettungsdienst (Emergency Service, G)	4.06
Polizei (G)	2.35
Pistensignal (Runway Signal G)	1.79
UK Fire Brigade	1.54

2.4.8 Psychoacoustic – Localisation

A localisable sound has characteristics that allow accurate detection of the direction by the listener [2]. The human brain is capable of localising sounds within 5° of accuracy [3]. It is obvious that one of the primary attributes of a siren signal is that the sound is localisable, so that road users and pedestrians can accurately detect the location of the approaching emergency vehicle [2]. The primary reason why drivers have difficulty determining the direction of the siren sound is due to the vehicle enclosure obstructing the direct path of the siren noise and redistributing the acoustic energy over the surface of the vehicle. This re-radiation of sound into the enclosed space in turn has an effect as it alters the apparent perceived direction of the sound source. One strategy to aid in solving this problem was enhancing the effective frequency range of sirens, as prior observations have shown that humans exhibit difficulty determining the location of pure tone sounds. Another approach to this issue was the implementation of low frequency siren systems that have increased vehicle penetration. This was due to the design of modern vehicles, which have high transmission loss above 1 kHz [20].

Another study was examined which made headway regarding the issues of localisation. It involved the comparison of four existing sirens (Yelp, Hilo, Wail, and Pulsar) to four newly developed sound patterns. The new patterns consisted of rapid frequency sweeps and each sweep was associated with a burst of broadband noise. The intention of using the new patterns was to increase localisation and alertness of siren systems. The study involved two components, first to test the sounds using a driving simulator and second to equip an emergency vehicle (in this case a fire truck) with these new patterns and record the reactions of drivers on the road in actual emergency vehicle journeys. Figure 10 shows the set up for the driving simulator jury testing [3] [28].

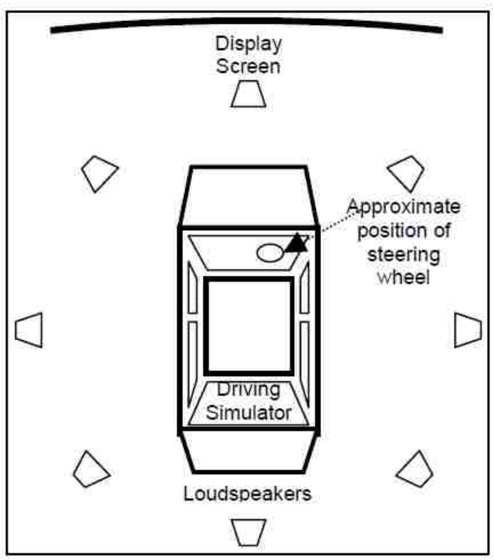

Figure 10: Layout of speakers in respect to the driving simulator for laboratory-based research [3]

The data obtained from the laboratory jury evaluations indicated that the new sound patterns had significantly improved localisation attributes. The results in Figure's 11 and 12 illustrate the scores of the subjects. For the left/comparison, the responses were considered correct if they were accurate within ±22.5° [3] [28].

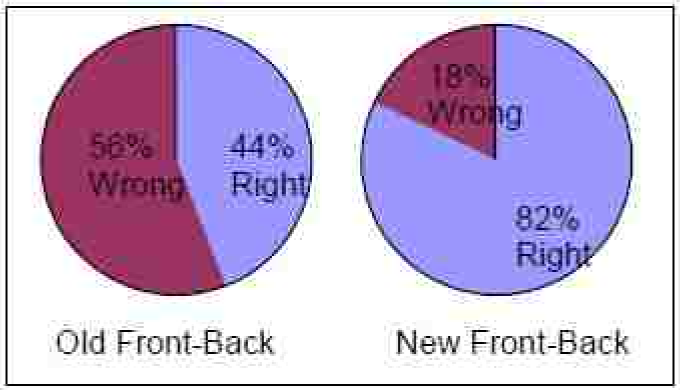

Figure 11: Percentage of correct responses for front/back detection [3] [28]

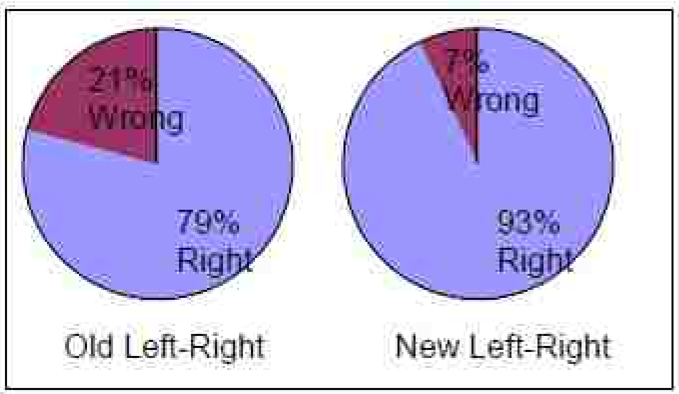

Figure 12: Percentage of correct responses (within ±22.5°) for left/right detection [3] [28]

As mentioned, the next phase of the study was the field trials, where the existing siren patterns along with the new patterns were installed on a fire truck and sounded during actual journeys. A video-recording apparatus provided an objective record of the interrelationship between the emergency vehicles and the road users. An onboard observer was also present to understand and note the actions taken by the road users. Also recorded were parameters that may affect the results such as weather conditions and route of journey. Precise notes during these journeys were recorded which were based on a set of ten variables highlighted as relevant to the experience of both the fire crews and road users during an emergency vehicle situation. Figure 13 presents a summary of the three most-relative parameters with the corresponding gathered data [3].

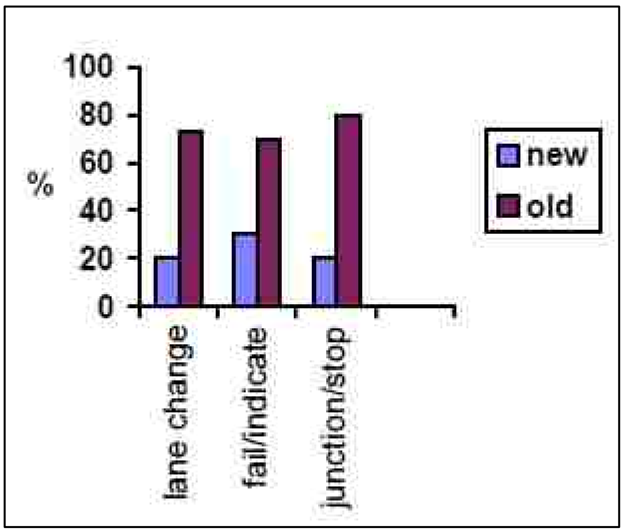

Figure 13: Percentage of events occurring in field trials [3]

This information revealed much information about the journeys during the field-testing. First, with the current (old) sirens, the fire trucks had to make more lane changes based on inappropriate road user responses. More road users also failed to indicate their intended direction of travel when using the old siren pattern. Finally, the fire trucks had to make over four times more stops due to issues associated with the limitations of the old siren sounds. All of the remaining variables yielded similar results, and thus overall road users reacted quicker, resulted in more appropriate, well-signaled manoeuvers.

Furthermore, employing the new siren sound patterns resulted in a reduction in journey times by as much as 8.5% [3].

2.4.9 Psychoacoustic – Alertness

Alertness is another relative psychoacoustic factor, which is often confused with perceived urgency. Alerting signals attract the listener's attention [3] [28]. It is also worth noting that, alerting and alarming are often used interchangeably, although they are not synonyms. The study discussed in the previous section also had the jurors rate the alerting nature of the old and new sirens on a 1-5 scale. The observation was that the new sound patterns scored equally as well, even though the participants were unfamiliar with the sound patterns [28]. This study confirmed that being accustomed to the sound did not play a vital role in the level of alertness.

2.4.10 Psychoacoustic – Masking

Masking is the effect of the reduction of the perceived loudness of a sound due to background noise and it can be calculated using the Critical Band Method [2]. Previous work had suggested that the SPL of a siren within a vehicle cabin be approximately 72 dB, for interior quiet conditions. With an assumed 30 dB attenuation provided by the closed car, the SPL outside the car must be above 100 dB. It was important to note that this requirement was for quiet interior conditions, as this was rarely the case with modern car audio and HVAC systems. As discussed, the sound power level of several sirens may exceed 120 dB, but the SPL at the drivers' door of a passenger vehicle was unlikely to be in excess of 100 dB [20]. Figure's 14 and 15 confirm this suspicion.

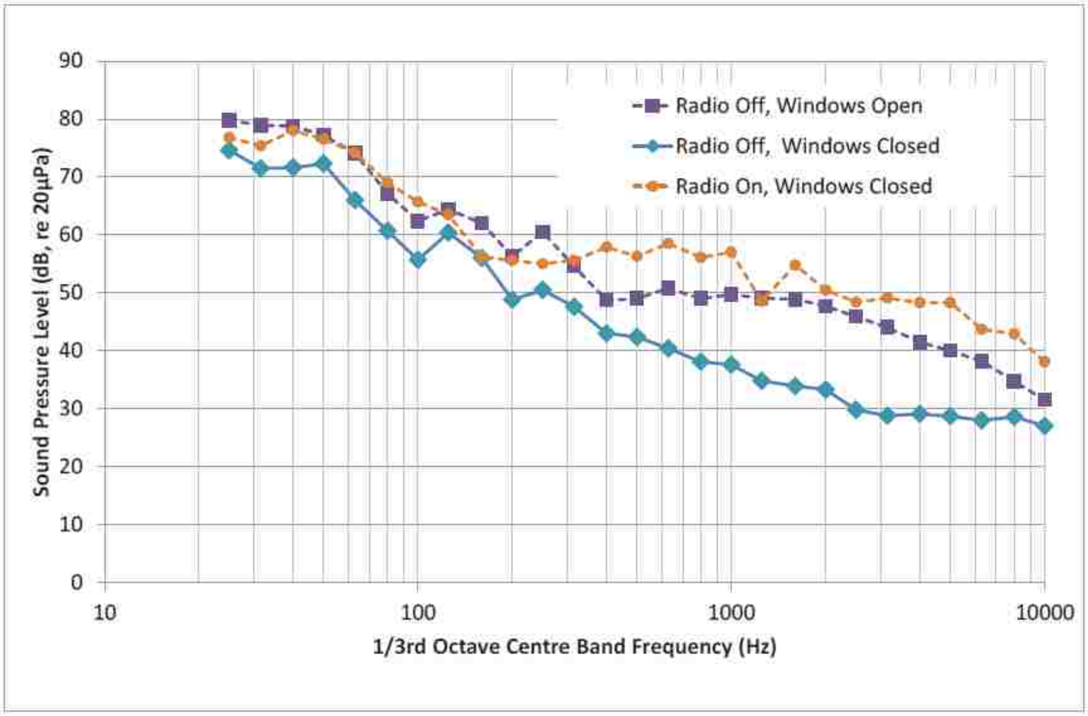

Figure 14: Masked thresholds under different conditions over 30 seconds [20]

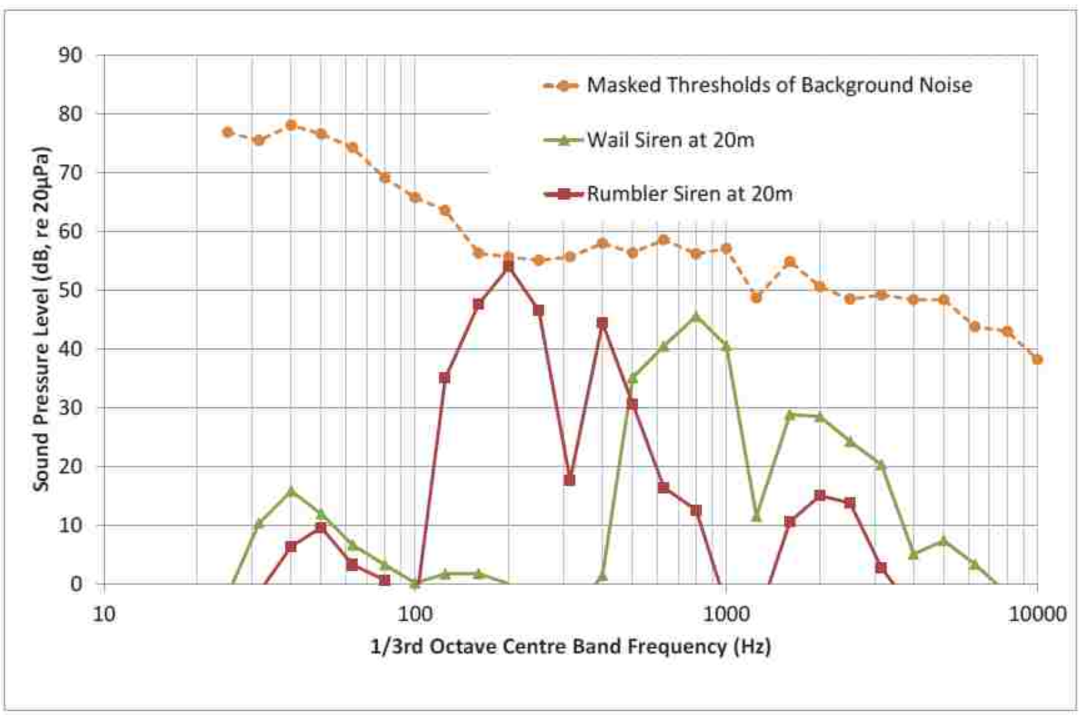

Figure 15: Masked threshold SPLs when driving with the radio on and windows closed and the predicted in-vehicle siren SPLs [20]

As seen in Figure 14, the masking thresholds were notably high in the frequency range of standard sirens and it is unlikely that the sound would be easily heard within the vehicle cabin under these conditions. From Figure 15, the masking thresholds were higher than both the Wail and the Rumbler siren. In general, a signal is less affected by masking if it is relatively complex in its nature and has a relatively large contrast with the background noise. It was stated that signal levels 6-10 dB above masking thresholds will ensure complete detectability. However, the recommendation was that signal levels be approximately 15 dB above the masked thresholds in order to ensure a rapid response from the listener [20].

2.4.11 Mounting Locations

Traditionally, the mounting of the siren devices has been on the front bumper, facing forward on an emergency vehicle. The past studies mentioned had concluded that a significant reduction in SPLs at perpendicular angles occurred, which resulted in the installation of additional loudspeakers in the wheel arches. A third location for the device was on the roof of the vehicle. A study to evaluate the positioning effect measured the A-weighted SPL inside the vehicle cabin for three Wail siren speaker locations. Table 3 shows the summarized data [29].

Table 3: Total A-weighted siren SPLs within the emergency vehicle cabin [20]

Position	Total Sound Pressure Level (dBA, re 20μPa)
Current Position on Front Bumper	71
Roof Location	79
Front Wheel Arch	72

Based on this data, the roof location was not an acceptable choice as a clearly perceptible increase of 7-8 dB occurred. This is notwithstanding the fact that emergency vehicle operators and crews currently have difficulty communicating with one another now with the current the siren locations on the bumper and in the wheel arch [20].

2.5 What is Missing?

While it is evident that significant amount of previous research on the topic of EVSN exists, it is clear that it requires more study. Some of the studies described above covered all aspects of the parameters of interest, while others are missing significant components. It is also apparent that the analysis of all the possible factors affecting EVSN effectiveness is incomplete. The overall missing link between most of these studies is the lack of comparison of major types of sirens and as well as investigations into major factors believed to hinder the siren's effectiveness. Many of the studies compare certain modes of the siren, such as the Wail and Yelp, but there exists little major work regarding a comparison of the major devices.

Based on the literature review perhaps the most incomplete study examined was regarding shadow effects. Much work devoted to acoustic barrier wall studies exist; however, the information focused on the effects of vehicle shadowing is very scarce. It was determined that vehicles did act as barriers towards siren noise, and that frequencies above 1000 Hz have less refracting capabilities [2]. However, little data is available regarding factors that may play significant roles in the effect of vehicle shadowing. These factors include: size of vehicle, location of vehicle (in line with receiving vehicle or pedestrian), position of vehicle relative to siren (parallel or perpendicular), and effects of different mounting locations of sirens.

A fundamental comparison regarding the traditional mechanical siren system and the newer electrical system appears to be absent as determined during the initial research and it is considered vital as the electrical systems are rapidly replacing the mechanical systems. Another major missing component of siren research was a more in-depth analysis of the newly developed low frequency systems. The occurrence with which adoption of systems occurs is increasing, yet with limited research validating the system. Along the same lines of additional siren systems, research pertaining to the air horn siren was incomplete and the conclusion is that the system has virtually no data proving its effectiveness or hindrance.

A final component that is absent from previous work is an overall recommendation regarding the most effective type(s) of siren systems for different emergency vehicles under different circumstances. The consensus based on the literature review is that each study only examined a fragment of a siren's characteristics and as a result, an overall recommendation in relation to the effectiveness is not evident.

CHAPTER 3

EXPERIMENT DETAILS

In order to perform a complete investigation of the effectiveness of the different types of emergency sirens, several experiments were developed. The experiments were broken into multiple parts, with each part focused on a different siren characteristic. The following chapter provides a complete and thorough description of the equipment and instruments used, as well as the associated environmental considerations, experimental design, preparation work, and experimental procedures followed for each experiment.

In terms of specifics regarding the actual equipment and procedure, the SAE's report, specifically pertaining to EVSN recommended practice, was reviewed. This report covers information pertaining to the types of microphones to be used, calibration equipment and techniques, test speaker and mounting, power supply, anechoic room, SPL measurements, frequency measurements, and cycling period, etc. [18]. These guidelines were followed throughout the course of this study as best as possible. In regards to health and safety, proper measures (such as earplugs) were taken to protect those involved in the testing.

The experiments for this investigation were separated into two parts. The first part was the measurement for future comparisons of a mechanical and electrical siren on a City of Windsor fire truck as well as the acquisition of the noise from a Rumbler siren installed on a City of Windsor Police Department cruiser that was donated to the University of Windsor for this study. From this data, analysis of the physical noise attributes was made. The second part investigated the psychoacoustic outcomes from these measurements through objective sound quality metrics as well as subjective evaluations of the sirens sounds.

3.1 General Experimental Setup

The general setup in terms of equipment and instrumentation for each of the experiments was similar. As such, the details given are common to each. Any changes or modifications to the procedure of any specific measurement will be discussed in detail within the appropriate related experimental section.

Given the psychoacoustic emphasis of this work, all of the acoustic acquisition was done using a Bruel & Kjaer (B&K) Type 4128-C binaural Head and Torso Simulator (HATS). The HATS is essentially a mannequin that has microphones mounted inside the ear cannel of the mannequin's ears. The reason for using the HATS is to provide better replication of the sound field at the receiver location of a person. This is particularly important if the playback of the signal will be used for jury evaluations. For the experiments, the HATS was positioned either in the driver's seat of the receptor vehicle or on a tripod to represent a pedestrian. The receptor vehicle was a 2010 Ford Focus Sedan. The two setups are shown in Figure 16.

Figure 16: HATS setup in receiver vehicle (left) and on tripod (right)

To acquire and record the noise data, the HATS was connected to a B&K LAN-XI data acquisition front end and the recordings were taken using B&K PULSE Time Data Recorder software. Prior to all data collection, the measurement system was field calibrated. Calibration tones were also recorded for the future calibration of the replay of the sounds. The sirens were operated and recorded for periods ranging from 5 to 30 seconds depending on the type of test being conducted.

Due to the physical space required to conduct the experiments, all measurements were conducted in wide-open outside areas, where background noise was a minimum so as not to affect the quality of the data. All measurements were made under appropriate weather conditions, which included dry ground surface and wind speeds under 15 km/h. These conditions were measured before each experiment and again after to ensure consistency.

3.2 Mechanical v. Electrical System Comparison & Analysis with the Rumbler

3.2.1 Equipment and Instrumentation Setup

The vehicles and equipment used for the experiments are categorised into three parts: those associated with the source, those associated with the receiver, and those associated with the barrier being tested (when applicable). The first emergency vehicle used was a City of Windsor Fire and Rescue Services Spartan fire truck. This truck was equipped with both the mechanical and electrical siren systems. The second emergency vehicle used for the testing was a Ford police cruiser donated to the University of Windsor by the City of Windsor Police Services. The vehicle was equipped with an electrical siren capable of both the Wail and Yelp as well as the Rumbler siren. The sirens tested were the Wail alone, Wail with the Rumbler, and Yelp with the Rumbler.

3.2.2 Environmental Considerations

The experiments were conducted at The Windsor International Airport on a private access road (formally Lauzon Road) at the east end of the property. This location was ideal, as it was sufficiently isolated to minimize any background noise from nearby traffic.

3.2.3 Experimental Design Setup and Procedure

Three experiments were conducted, which were designed with the intention of acquiring all the necessary data in the least possible time. The reason for this was due to the limited time that the fire truck was available. The engines for all the vehicles involved in the test were idling during the experiment, unless otherwise stated. Only a single recording for each part of the each experiment was made, again due to the limited period available for data acquisition.

3.2.3 a) Shadow Phenomenon

The first test was to investigate the impact of the shadow phenomenon. For this, only the intersection (off-axis) scenario was examined. A schematic of the experimental setup for the shadow testing is shown in Figure 17. The arrows associated with each vehicle represent the vehicle's orientation and the distances measured were from the source to the receiver. Recordings were acquired using the HATS, which was placed inside the receiving vehicle and the PULSE acquisition system. The barrier vehicle used was a 2006 Toyota Sienna.

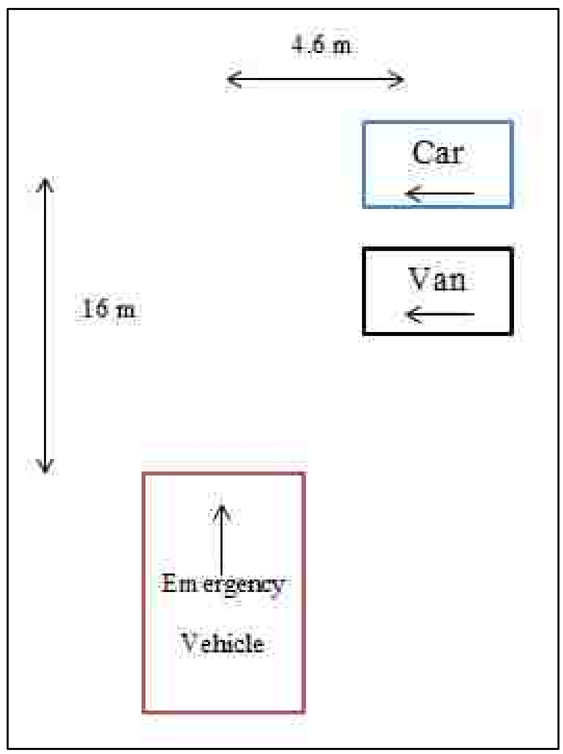

Figure 17: Shadowing setup with emergency vehicle

The procedure for the shadow experiment is as follows:

1) The vehicles and equipment were positioned as shown and discussed above.
2) Equipment calibrations were performed and calibration tones recorded.

3) i. Mechanical and electrical sirens were each operated for a period of 7-15 seconds and recorded.

   ii. The Wail, Wail with Rumbler, and Yelp with Rumbler were each operated for a period of 7-15 seconds and recorded.

4) The shadow vehicle was removed and Step 3 is repeated.

3.2.3 b) Pass-by

The second experiment conducted was the vehicle pass-by (drive-by) test. This test was designed to simulate the emergency vehicle approaching an intersection at 50 to 60 km/h for the fire truck and police cruiser respectively and passing by a stopped vehicle, which is positioned perpendicular to the direction of travel of the emergency vehicle. A schematic of the experimental setup is shown in Figure 18.

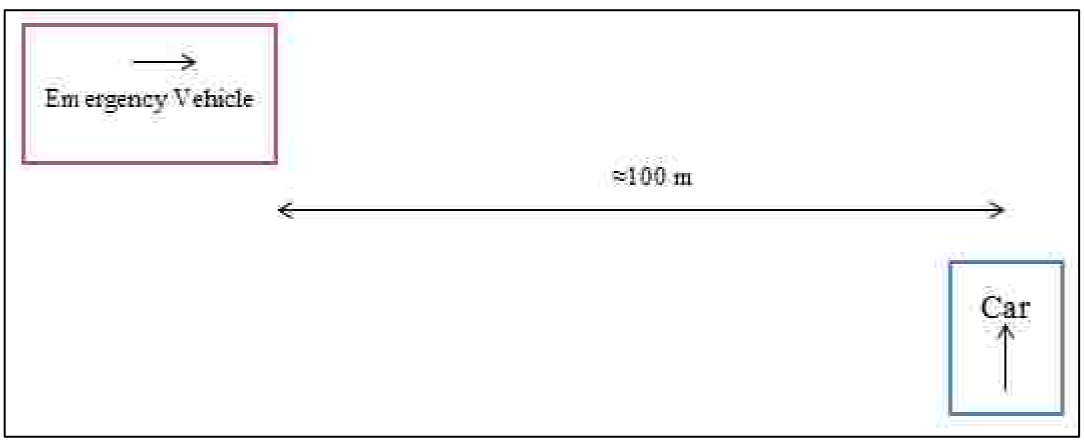

Figure 18: Pass-by setup

The procedure for the pass-by tests is as follows:

1) The vehicles and equipment were positioned as shown and discussed above.
2) Equipment calibrations were performed and calibration tones recorded.

3) The emergency vehicle accelerated until the predetermined speed of 50 or 60 km/h was reached, at which point it maintained this speed.

4) i. As the vehicle began to accelerate, the mechanical and electrical sirens were each operated until after the emergency vehicle completely passed the receptor vehicle. It should be noted that this step was repeated with the simultaneous and continuous addition of the air horn.

   ii. As the vehicle began to accelerate, the Wail, Wail with Rumbler, and Yelp with Rumbler were each operated until after the emergency vehicle completely passed the receptor vehicle.

3.2.3 c) In Front Directivity

The third experimental setup was designed to investigate the frontal directivity characteristics of the siren systems. For this experiment, the HATS was positioned around the emergency vehicle with 180° coverage. It was decided that there was little point in evaluating the rearward direction of the sirens given that sirens are intended for frontal warning. The setup for this experiment is shown in Figure 19. For the fire truck measurements, the HATS was located 8 m from the centre of the fire truck front bumper, whereas for the police cruiser, two test distances of 5 and 10 m from the centre of the front bumper were evaluated. The second distance for the police cruiser was to investigate the reduction of the Rumbler noise at a magnitude doubling of the source-to-receiver distance.

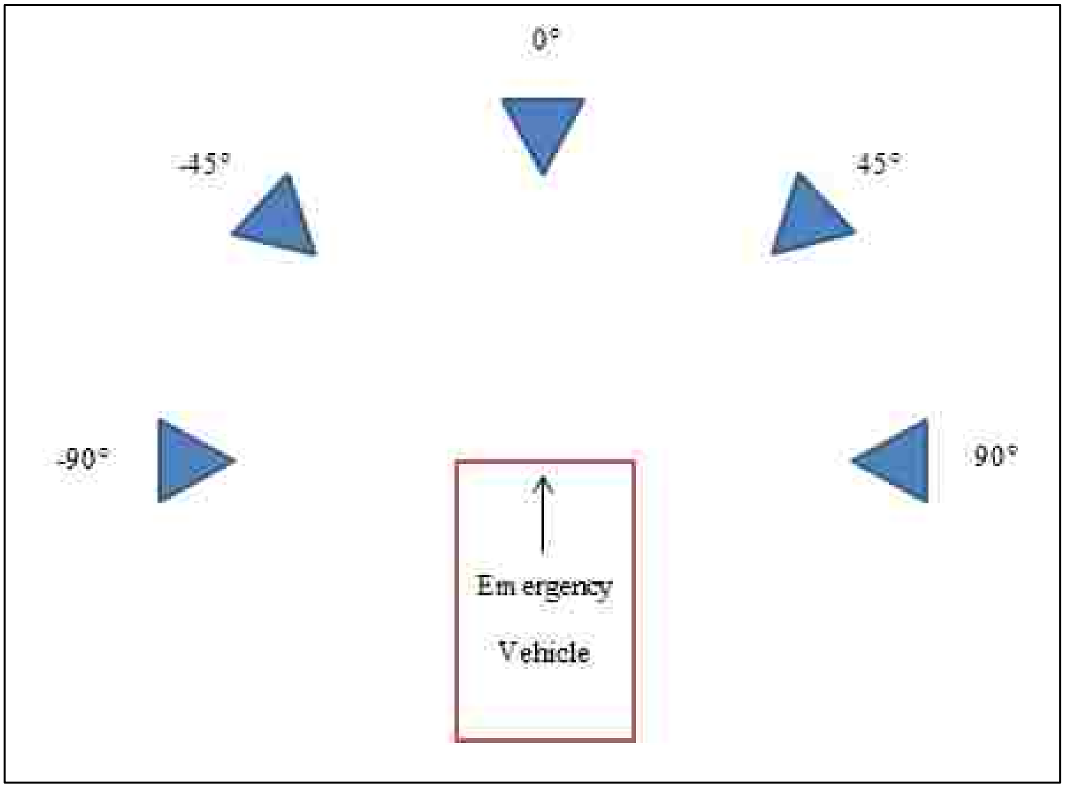

Figure 19: Frontal directivity setup

The procedure for the frontal directivity experiment is as follows:

1) The vehicles and equipment were positioned as shown and discussed above.
2) Equipment calibrations were performed and calibration tones recorded.
3) i. The mechanical and electrical sirens were each operated for a period of 7-15 seconds and are recorded.

   ii. The Wail, Wail with Rumbler, and Yelp with Rumbler were each operated for a period of 7-15 seconds and were recorded.
4) The HATS device was then moved to the next radial position and Step 3 was repeated.
5) Steps 3) ii. and 4) were repeated at a second distance of 10 m.

3.3 Psychoacoustic Analysis using Objective Sound Quality Metrics & Subjective Testing

Once the recordings were processed and analyzed, the next phase was to perform objective testing using sound quality metrics allowing for comparison to the outcome from human jury evaluations. Prior to the evaluation, psychoacoustic metrics were calculated using sound quality software, to aid and design the jury evaluation. The majority of the recordings made in the Stage 1 testing were used for the jury evaluation playback. For this, a vehicle buck NVH driving simulator was used. For the jury testing, an application was submitted and approved by the University of Windsor Ethics Board. A copy of the Consent Form is provided in Appendix A.

3.3.1 Equipment and Instrumentation Setup

The jury test was conducted using a buck simulator that was designed and built by undergraduate students as a Capstone Design project. The purpose of using the buck with the NVH simulator software is to better simulate the driving experience and add context to the tests. A photo of a juror performing a test in the simulator buck is shown in Figure 20. The simulation scenario was designed to be located at a 3-way traffic intersection, such that traffic was moving in the left and right directions in relation to the juror. Traffic lights were set to correspond to normal traffic situation with the traffic lights changing from green, to yellow, and to red, and then repeating for all directions of travel. For this study, the subject was positioned such that they were stopped at the intersection and they were instructed to remain at this location regardless of the colour of the traffic light.

Figure 20: Juror in the NVH driving simulator buck participating in evaluation

The recordings were organized into two main categories; comparison of the fire truck's electrical and mechanical sirens and the analysis of the police cruiser's Rumbler siren. The recordings were edited using Brüel and Kjær PULSE LabShop Time Edit software to correct for appropriate left and right headphone balance. This was to ensure that the recordings are replayed to the correct ear and at the proper level in relation to one another. At this point, the recordings were subsequently resampled at 44100 Hz as required by all sound quality metric calculations.

Prior to each jury test, the playback headphones were calibrated to ensure the recordings were being replayed to accurately represent the original sound recorded in the field. To calibrate the headphones, the simulator headphones were positioned on the HATS and a 94 dB calibration tone recorded during the initial data acquisition was played through the headphones using the desktop simulator software. Here, the simulator sound mixer was adjusted until a level of 94 dB was measured by the HATS microphones (at each ear). Other factors of interest such as temperature of the room and comfort environment were considered and monitored during all jury evaluations.

3.3.2 Environmental Considerations

The subjective testing was carried out in a private room located in one of the NVH research labs. The testing environment was set such that the subject was comfortable to increase the concentration of the juror and to reduce possible sources of error. The noise level within the room was kept to a minimum level well below the detectable threshold of the headphone-wearing juror. Lighting and temperature were adjusted to a comfortable and constant level throughout the test to ensure that the participant did not experience fatigue and/or annoyance during the test.

3.3.3 Experimental Design Setup and Procedure

The jury tests were conducted using a predetermined list of sounds presented to the participants while they sat in the NVH driving simulator, which was positioned at an intersection in the stopped position at a traffic light. The participant was not required to drive the vehicle in motion. For the jury tests, only the pass-by and shadow phenomenon experimental data, using both the electrical versus mechanical comparison and Rumbler siren data, were used for these tests. The subjective test was comprised of 32 A/B paired comparisons, 16 of which were inverted duplicates. A copy of the test sheet used for the experiment is provided in Figure 21, which was completed by the research investigator.

The comparisons were randomized to avoid the juror becoming accustomed to any of the signals. Not mixing up the signals from one participant to the next ensured that each person was given an identical test under the same conditions. The test instructions were also provided to and verbally given to each participant. The matrices, which illustrate all of the paired signals used for the evaluation, are given in Appendix B.

M.A.Sc. - EVSN Effectiveness Loudness Analysis - Jury Evaluation

Subject #:
Date of Evaluation:

Birth Date of Juror:
Gender of Juror: M F

Introduction:

The purpose of this evaluation is to evaluate the perceived loudness of different sirens under different traffic conditions. For example: during some of the comparisons you will be listening to the same signal under different conditions and for others you will be comparing different siren sounds simulating traffic situations. The siren signals have been randomized to avoid becoming accustomed to any of the signals. If you would like to take a break at any point during the exam, please feel free to do so.

Test Instructions:

1. Now that you have signed the Consent Form and been briefed on the test, we can begin the evaluation
2. First, I will enter the driving simulator and position the vehicle such that an intersection scenario is present
3. I now ask you now to enter the simulator and adjust your seat such that you are as comfortable as possible
4. Once comfortable, shift into 1st gear using the throttle on the right side of the steering wheel while keeping your foot on the brake
5. To conduct the test you must use the touchscreen monitor to your right
6. Select A from the top option on the monitor to load the 1st siren signal to be played
7. Press the small red button on the left side of the steering wheel to play the loaded siren signal
8. Now select B from the top option on the monitor to load the 2nd siren signal to be played
9. Again press the small red button on the left side of the steering wheel to play the loaded siren signal
10. Now that you have listened to both of the siren signals, select which you perceive to be louder using the A or B options on the bottom of the monitor
11. Selecting your choice records your answer and loads the next paired test (now you have to select A at the top of the monitor to load the siren, press the button the play the signal, and so forth)
12. In addition to selecting your option on the bottom of the monitor, I ask that you verbally communicate your option to me so that I can physically record it
13. If you don't have any questions you can now put the headphones on (making sure they are on the correct ears) and we can begin the test

Select the signal that you perceive to be LOUDER:

1.	A	B	17.	A	B
2.	A	B	18.	A	B
3.	A	B	19.	A	B
4.	A	B	20.	A	B
5.	A	B	21.	A	B
6.	A	B	22.	A	B
7.	A	B	23.	A	B
8.	A	B	24.	A	B
9.	A	B	25.	A	B
10.	A	B	26.	A	B
11.	A	B	27.	A	B
12.	A	B	28.	A	B
13.	A	B	29.	A	B
14.	A	B	30.	A	B
15.	A	B	31.	A	B
16.	A	B	32.	A	B

Figure 21: Jury evaluation test sheet

CHAPTER 4

DATA ANALYSIS

4.1 General Analysis Outline

Following the data acquisition described in the previous chapter, a thorough analysis of the data was carried out. This was done using several software applications as well as good engineering practices as are described in this chapter.

Once acquired using the PULSE Time Data Recorder software, the data was post-processed using B&K PULSE Reflex software, and exported to Microsoft Excel for organization and graphing. Two analysis techniques were used to process the data, those being a frequency analysis and a time analysis. The frequency analysis was performed through the use of the Fast Fourier Transform (FFT), which produces a frequency domain representation of the time domain signal. The frequency range chosen was based on the effective frequency range of the sirens as specified by the manufacturer. The second analysis technique was an overall time analysis, which allows for the analysis of the noise amplitude over time. For this, A-weighting filters were applied to the data to better represent the perceived amplitude of the sounds, particularly at low frequencies.

Once the data was post-processed using the Reflex software, it was exported into Microsoft Excel. Here, the left and right ear data were combined into one overall value and then plotted into either a scatter or a radar plot for examination. These plots were used to compare the different siren sounds and to make conclusions as to the effectiveness of each siren scenario. A subsequent subjective analysis was performed to validate the objective conclusions and to provide insight into the human perception of the different sirens under the different tested conditions and scenarios. Only some of the resulting data is presented in this chapter for discussion with the remaining results given in Appendices C and D. The flowchart below illustrates how each of the signals were compared against one another for each of the experiments.

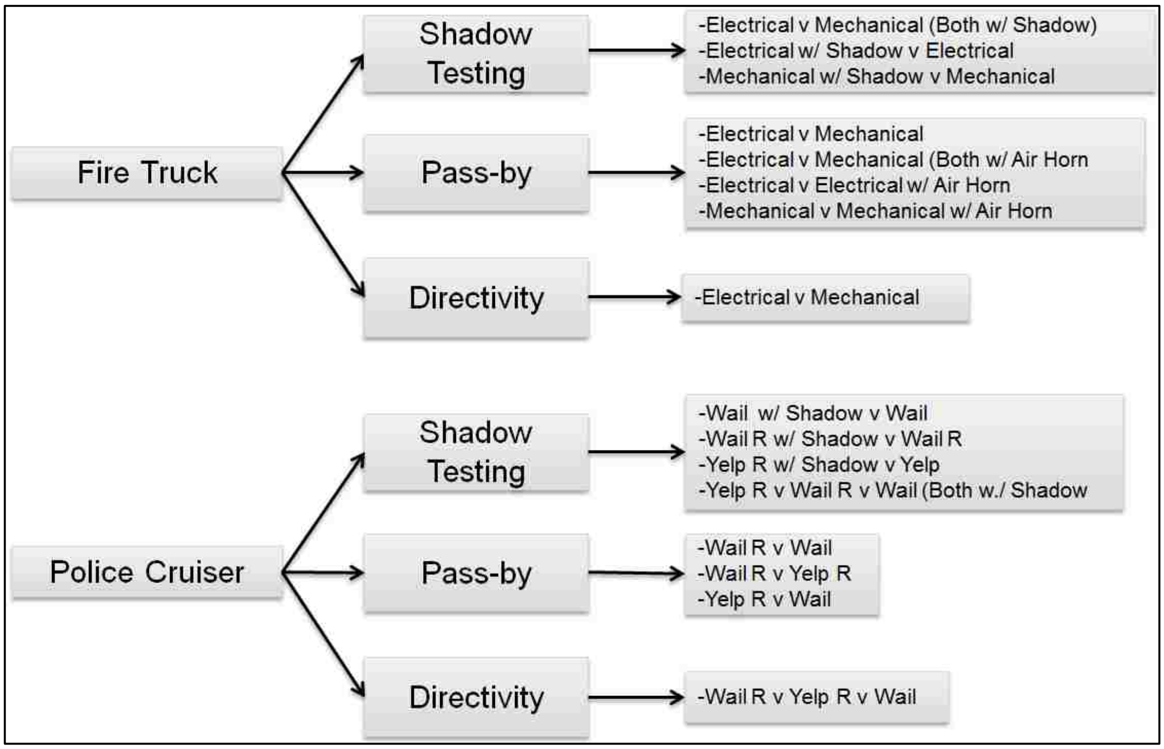

Figure 22: Flowchart of signals to be compared against one another for each test

4.2 Mechanical v. Electrical System Comparison & Analysis with the Rumbler

As discussed in Chapter 3, this component of the research involved three different experiments for which the overall and frequency analysis techniques were used to post-process the data.

4.2.1 Mechanical v. Electrical System Comparison

From the manufacturer, the stated frequency range for the e-Q2B electrical siren is 725 to 1600 Hz [30]. No frequency range was available from the manufacturer of the mechanical siren but observations from the measured data indicated that it was very similar to that of the e-Q2B. As such, a common frequency range for analysis was used for all sirens.

4.2.1 a) Shadow Phenomenon

As mentioned in Section 2.4.2, a previous study [27] concluded that significant adverse effects resulted in the detectability of an emergency siren resulted from the presence of a shadow vehicle. This previous study however, had faults in how the data was collected. The investigation of the effect of a shadow vehicle was repeated in this study, only with using actual emergency vehicles at an intersection scenario and with much better ambient noise levels. Figure 23 is a graph of the measured frequency response inside a receiver vehicle during the operation of the electrical siren, with and without the presence of the shadow vehicle. The difference in sound level between the two cases exceeded 10 dB at some frequencies, which correlates to a change in loudness by a factor of two. At some frequencies, the difference between the two cases suggests a change in loudness by a factor as high as nearly four.

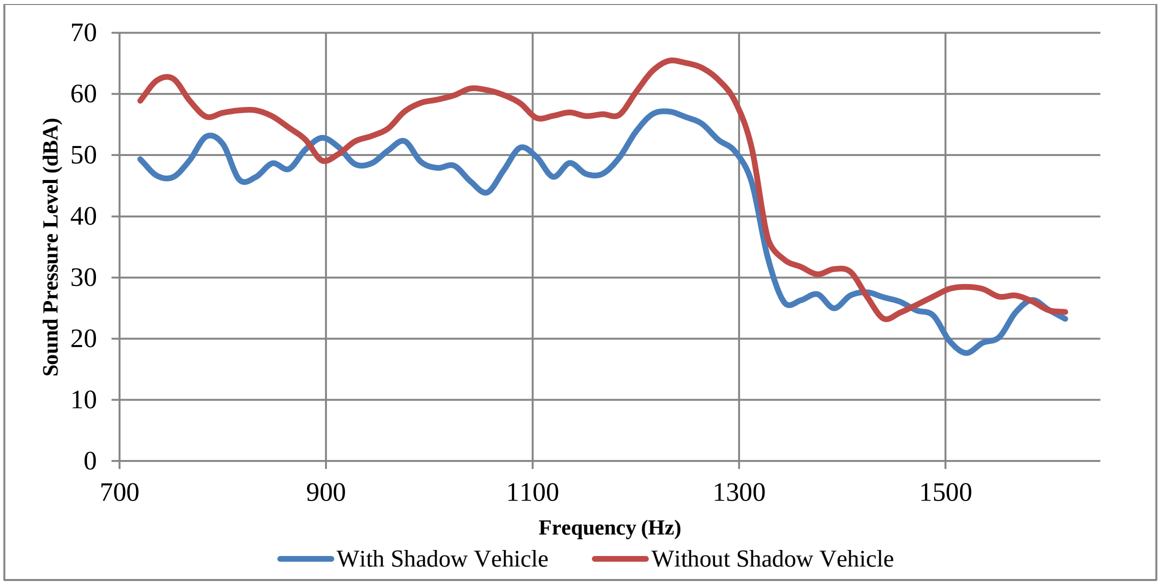

Figure 23: A-Weighted Frequency Response of the electrical siren inside the receiver vehicle with and without the presence of the shadow vehicle

Figure 24 shows the results of the same test, only this time using the mechanical siren. While the results do not mirror that of the electrical siren, the mechanical is generally affected in the same manner by the presence of a blocking vehicle. It is observed that the greatest difference in sound pressure was at the extremes of the siren's frequency range, at some frequencies greater than 30 dB.

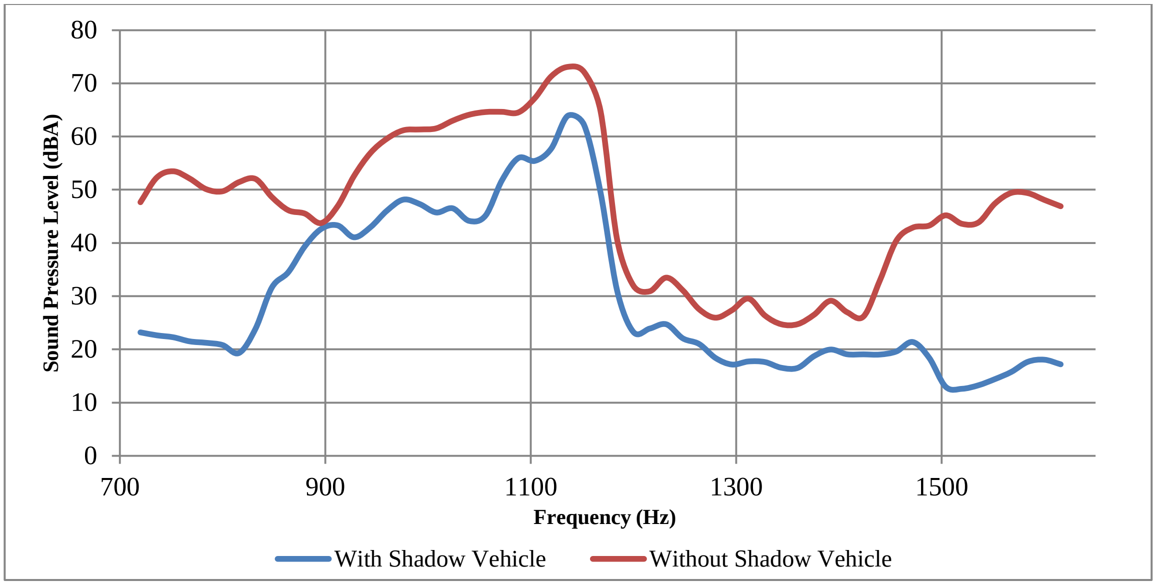

Figure 24: A-Weighted Frequency Response of the mechanical siren inside the receiver vehicle with and without the presence of the shadow vehicle

Given next is a comparison of the frequency response of the two sirens inside the receiver vehicle with the presence of the shadow vehicle. As can be seen in Figure 25, the electrical siren performed better at most frequencies over the mechanical siren, except between the frequencies of 1050 and 1175 Hz, where the mechanical siren showed an increase in sound pressure level, a spike was observed at approximately 1400 Hz.

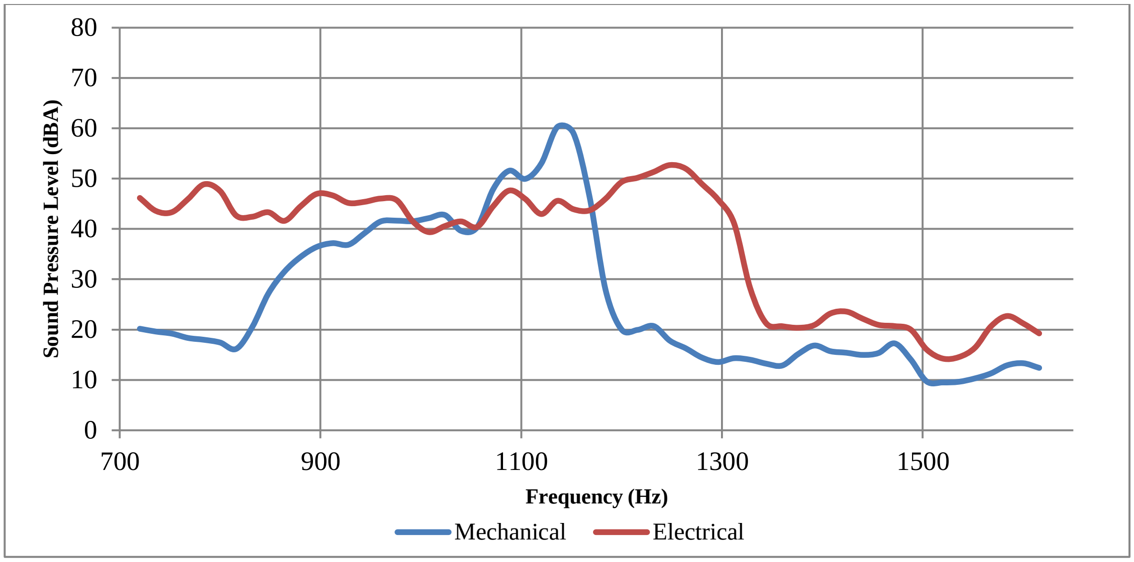

Figure 25: A-Weighted Frequency Response of the mechanical and electrical siren inside the receiver vehicle with the presence of the shadow vehicle

The same analysis was performed for the case without the shadow vehicle present. As this is not relevant to the effect of the presence of a shadow vehicle, this analysis was not included in the body of the report and instead is provided in Appendix C. Based on the presented data, it can be concluded that for the effective frequency range of the two sirens, the electrical siren generally outperformed the mechanical siren in terms of overcoming the effect of the shadow vehicle. However, the frequency spike observed for the mechanical siren in Figure 25 posed an interesting point given that the mechanical siren functions with a much more flat frequency response. This is attributed to the much smaller cycling period for the mechanical siren.

The next data presented is the overall sound levels versus time for the various measurement cases. It was shown previously in Figure 25 that the mechanical siren had a notable level increase around the 1150 Hz region; however, this analysis does little to show the magnitude of what impact this has on the overall effectiveness of the mechanical siren compared to the electrical siren. For this, similar comparisons using overall levels versus time are examined. To perform this, the data recordings were sliced into six-second segments to extract complete cycles of each siren for direct comparison. Again, analyses were carried out for the cases with and without the shadow vehicle present. Figure 26 displays the sound pressure level data for the time period of the two sirens with the shadow vehicle present. Also shown are the linear trend lines for each siren graph to aid in representing the average of the data values for comparison purposes. Logarithmically averaging the data was another option considered for the analysis. It is observed that while both sirens have fluctuating components, the mechanical siren demonstrated less modulation and is arguably more effective than the electrical siren.

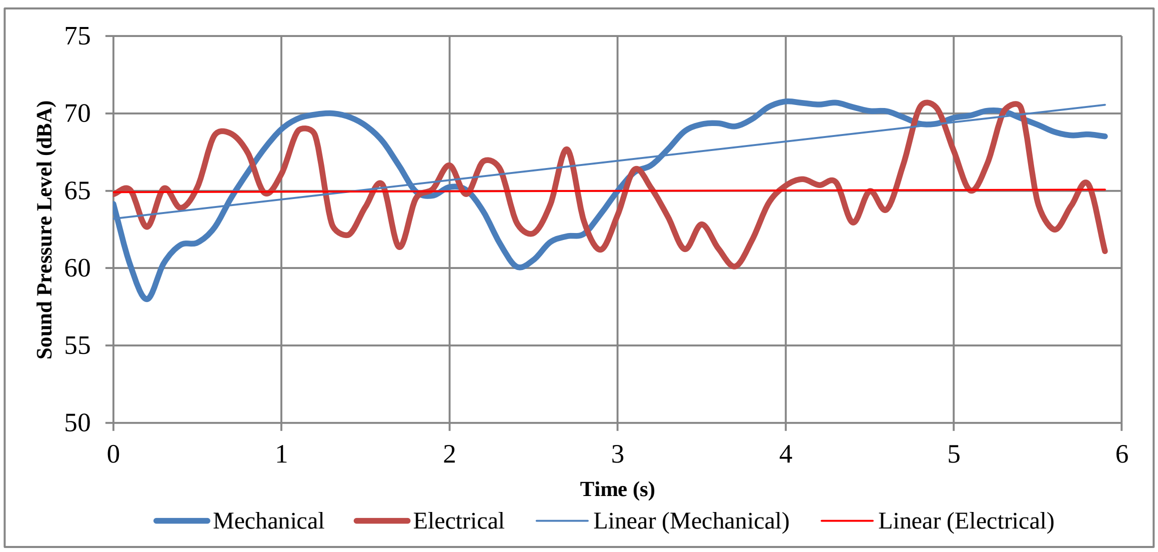

Figure 26: A-Weighted Overall Time Response of the mechanical and electrical siren inside the receiver vehicle with the presence of the shadow with corresponding linear

The next comparison is that of the overall time analysis of each siren signal with and without the presence of the shadow vehicle. Figure’s 27 and 28 illustrate the data for the electrical and mechanical siren systems respectively. The difference between the data with the shadow vehicle present and absent is approximately 12 dB for the electrical siren. It is important to note that the electrical siren fluctuates greatly in sound pressure level, with the maximum and minimum differences between the two cases being 20 and 4 dB respectively. In consideration of the mechanical siren, the arithmetic average difference between the presence and absence of the shadow vehicle was again 12 dB. The characteristics of the mechanical siren produced a more constant sound with differences between the maximum and minimum data values being 21 and 6 dB respectively. The mechanical siren showed two 'dips' in the sound pressure level, which are likely attributed to the warm up period of the siren, as drops of this magnitude in sound pressure level for the mechanical siren were very uncommon under normal operating conditions. Based on the data analysed, it is shown that the electrical siren is more affected by the presence of the shadow vehicle.

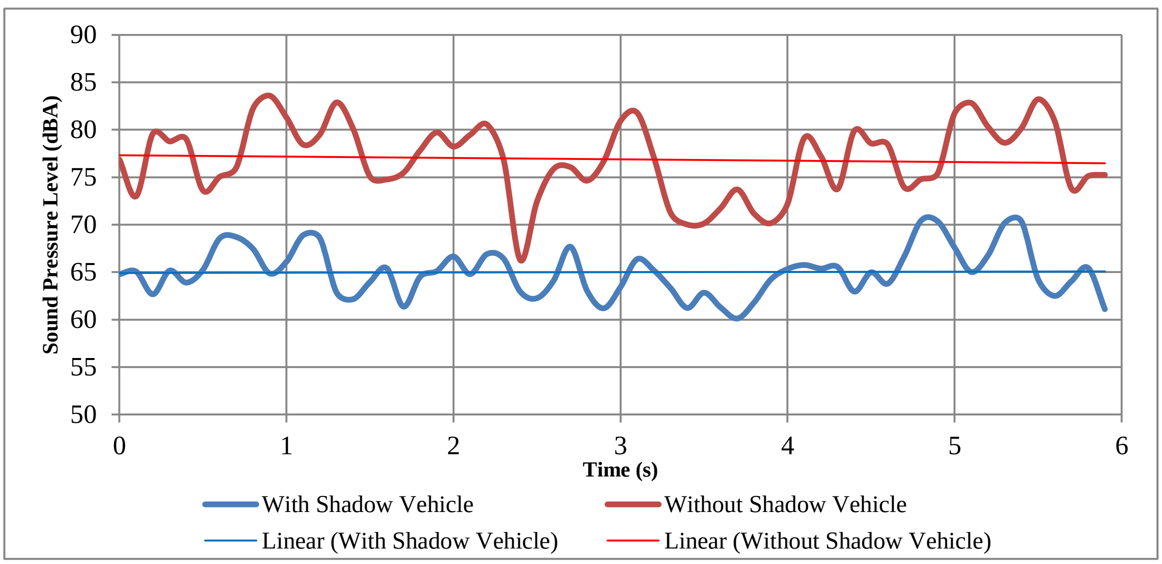

Figure 27: A-Weighted Overall Time Response of the electrical siren inside the receiver vehicle with and without the presence of the shadow vehicle with corresponding linear trend lines

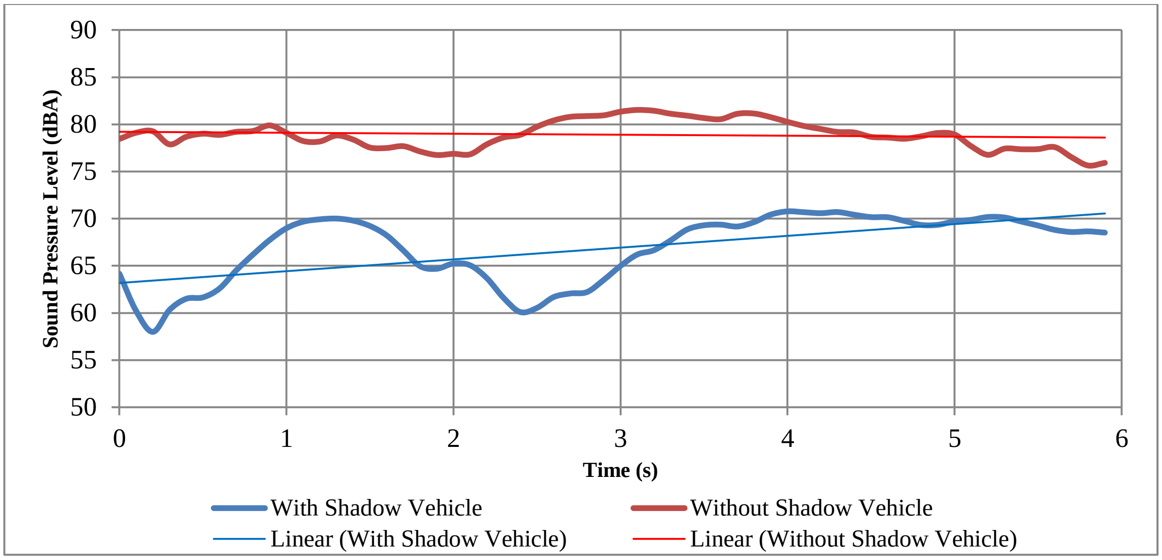

Figure 28: A-Weighted Overall Time Response of the mechanical siren inside the receiver vehicle with and without the presence of the shadow vehicle with corresponding linear trend lines

4.2.1 b) Pass-by

Next considered is the pass-by data where the emergency vehicle passed by the perpendicular receiver vehicle, which was positioned as if at an intersection. As it was difficult to record identical segments for each pass-by run, the data points are matched based on the peak values, which are viewed as the small time period just before the emergency vehicle passed by the receptor vehicle. It is important to note that is was not possible to acquire data for each signal at the same point in their corresponding cycle, i.e. the midpoint of the wavelength.

First examined is the direct comparison of the electrical and the mechanical siren systems as given in Figure 29. It is shown that the mechanical siren is generally louder than the electrical siren as the differences in sound pressure level at the maximum point is more than 7 dB. It was important to note that there are a few smaller spikes in the amplitude for the mechanical siren.

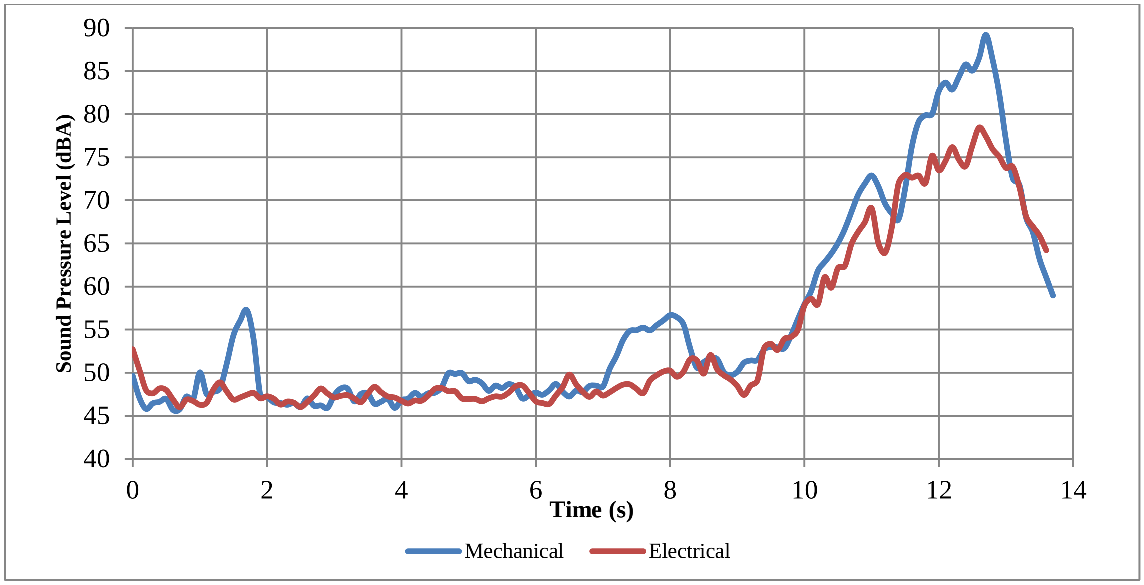

Figure 29: A-Weighted Overall Time Response of the mechanical and electrical siren pass-by inside the receiver vehicle

Next compared are the two sirens with the addition of the air horn system as given in Figure 30. The mechanical siren showed better performance over the electrical again at the maximum values, but the electrical siren is favoured for several seconds prior to the spike. This leads to the conclusion that the air horn in combination with the electrical system improved the output of the electrical siren at greater source-to-receiver distances, but not when in the nearest proximity to the receiver.

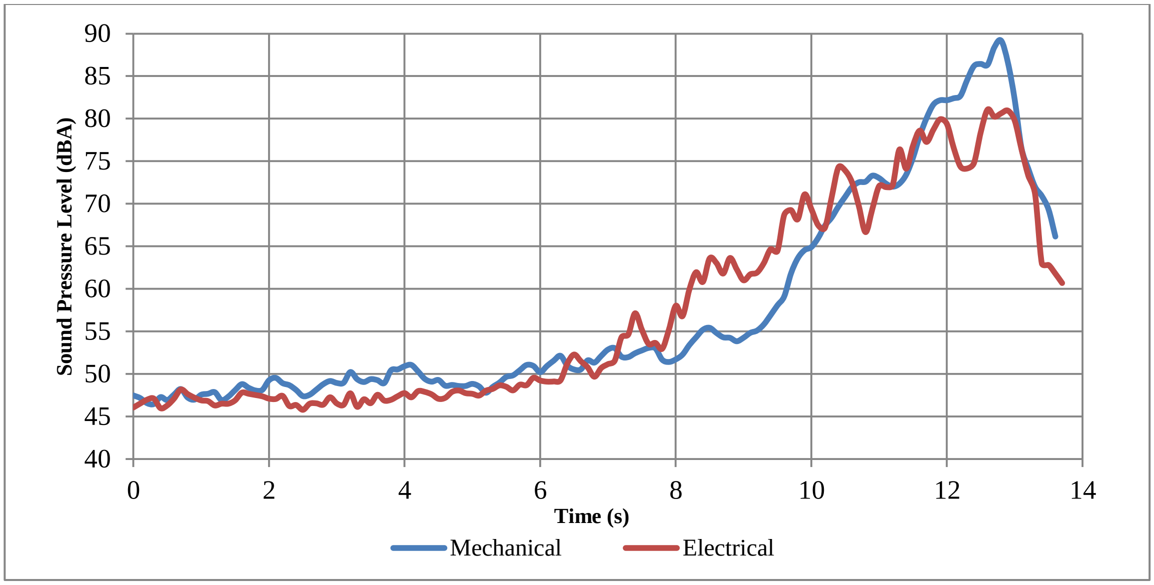

Figure 30: A-Weighted Overall Time Response of the mechanical and electrical siren pass-by with the air horn inside the receiver vehicle

The next comparison was the investigation of each individual siren with and without the use of the air horn system. The results are shown in Figure’s 31 and 32. The purpose of this was to validate or disprove the use of the air horn as an effective warning device when used in conjunction with a siren. Understandably, the addition of the air horn resulted in an increased sound pressure level in each case, particularly in the few seconds prior to the siren sound reaching the receptor vehicle. Examining Figure 31, the difference was approximately 5 dB and at some cases exceeded 15 dB, which amounts to a substantial change in sound level.

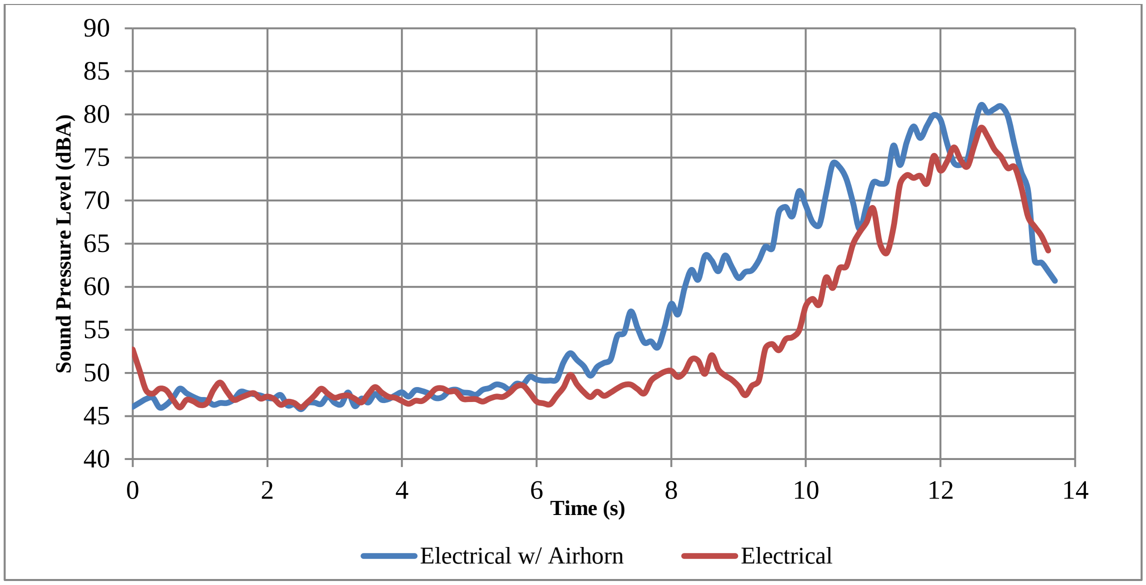

Figure 31 A-Weighted Overall Time Response of the electrical siren pass-by with and without the air horn inside the receiver vehicle

The results for the mechanical siren system are given in Figure 32 where it is seen that the air horn did not improve the siren system's capabilities to the same degree as with the electrical siren, likely because the mechanical system is already significantly louder than the electrical. This point supports earlier conclusions discussed from the data results shown in Figure 30, where the electrical siren outperformed the mechanical siren in the time period prior to the peak. Nonetheless, the addition of the air horn still proved to enhance the sound level for both siren systems.

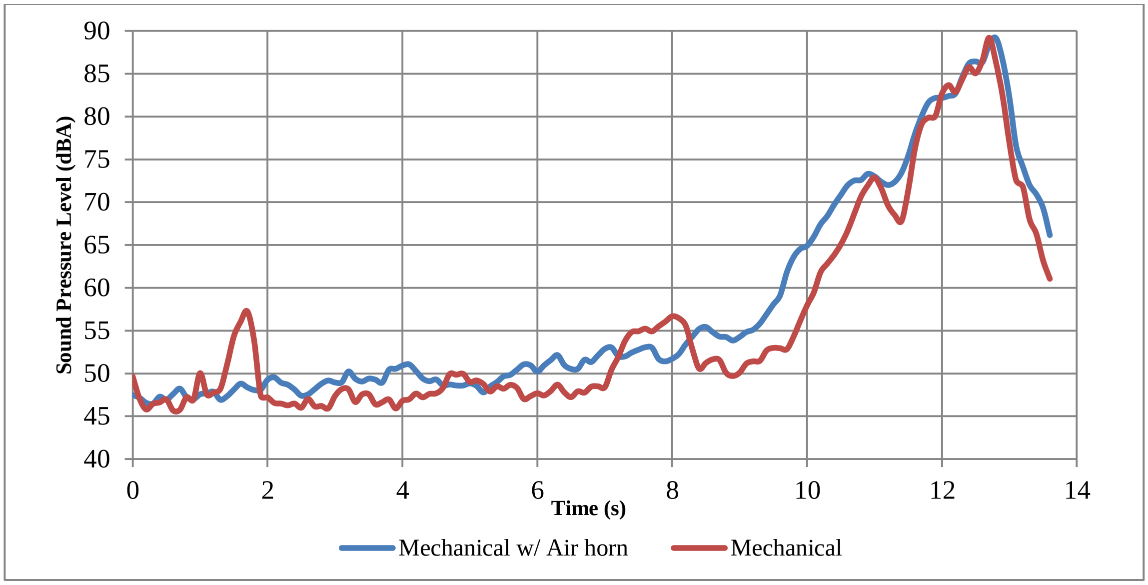

Figure 32: A-Weighted Overall Time Response of the mechanical siren pass-by with and without the air horn inside the receiver vehicle

Next examined was the frequency spectra averaged over the pass-by time for each siren. Shown in Figure 33 is the data for each siren without the air horn system activated. The results closely resemble the observations noted during the testing, as the electrical siren was observed to be most notable at the height of its cycle (at the lower frequencies) with its amplitude greatly diminishing as the low-to-high frequency increased. The frequency response for the mechanical siren was much different, as it did not possess the same high-to-low sweeping characteristics as the electrical siren. The majority of the mechanical siren's sound level was approximately 30-40 dBA until a 70 dB spike occurred at approximately 1200 Hz, where the sound pressure level was approximately 30 dB higher than the electrical siren.

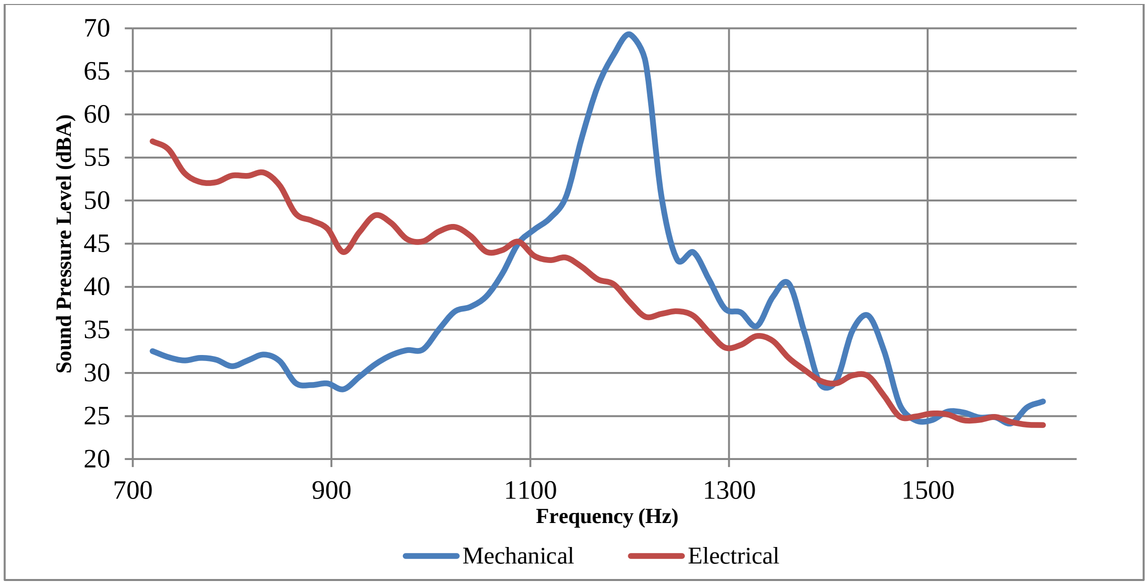

Figure 33: A-Weighted Frequency Response of the mechanical and electrical siren pass-by inside the receiver vehicle

While less critical, the same procedure was carried out with the addition of the case with the air horn siren system. Justification for which siren performed better was less conclusive, but at the same time, strengthened the case for use of the air horn. As seen in Figure 34, the majority of the data exceeded 40 dBA, unlike in Figure 33, where the majority of the data was below 40 dBA. The fluctuations observed for both sirens were due to the acoustical characteristics of the air horn (having a very short cycling period), when combined with each of the siren types.

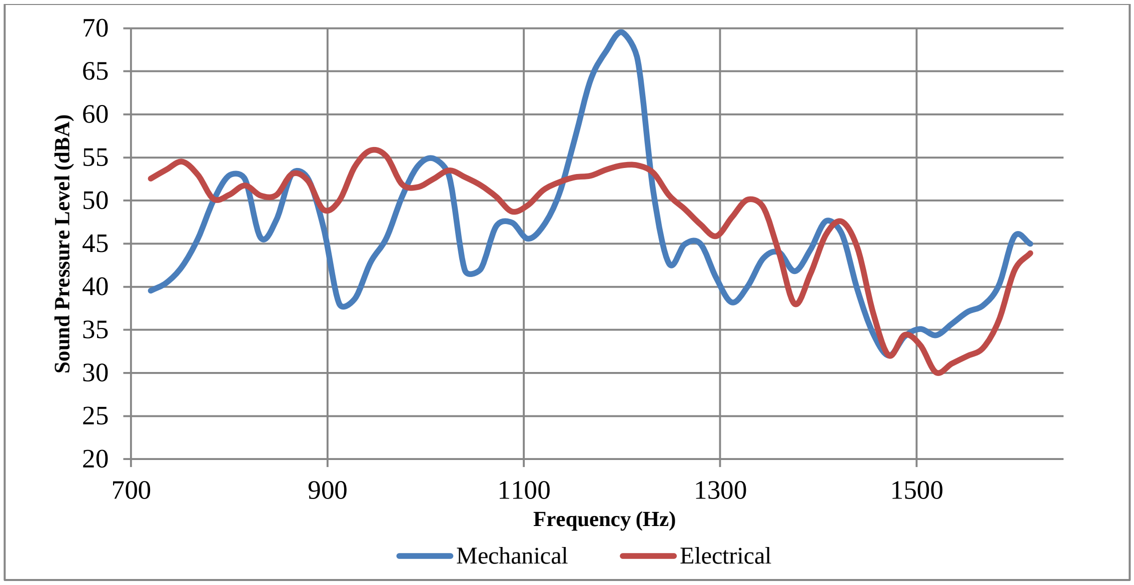

Figure 34: A-Weighted Frequency Response of the mechanical and electrical siren pass-by with the air horn inside the receiver vehicle

4.2.1 c) Directivity

Analysis of the sound pressure level data taken at the various radial directions was performed to determine the directivity of each siren case. From this analysis, the maximum, minimum, and mean sound pressure levels were determined for comparison.

The A-weighted radial data for the electrical siren is given in Figure 35 from which several observations can be made. Firstly, the data is relatively symmetric in the sense that opposing angles came close to mirroring each other. In addition, there is a substantial difference between the maximum and minimum values, particularly at the direct frontal measurement. Here, the difference in sound pressure level exceeded 20 dB. This difference can be described as having a perceived change in loudness by more than a factor of four and is attributed to the electrical siren’s modulation. Finally, it is important to note that the reported mean values occurred nearly at the midpoint for all the measurements, indicating that neither the maximum nor the minimum values are affected by outside factors, such as environmental background noise.

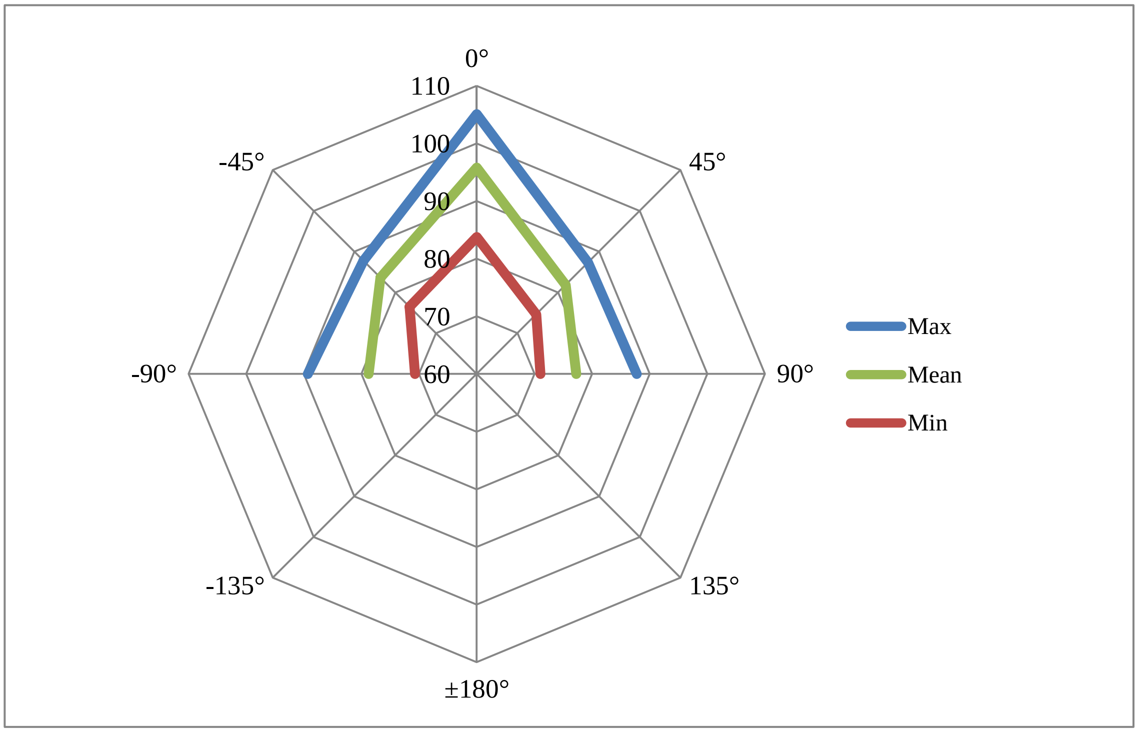

Figure 35: A-Weighted Overall Time Response of the electrical siren frontal directivity

The results for the same analysis for the mechanical siren are given in Figure 36. Significant differences between these two sirens are observed. An obvious observation from Figure 36 is that the differences between the three calculated measurements are relatively low with the largest difference being less than 6 dB, which while perceivable, is not nearly as significant of a change in sound pressure level compared to the electrical siren. This small fluctuation is likely due to the characteristic of the siren, which emits a much more constant sound output, as opposed to the rise and fall modulating effect from the electrical siren. Additionally, the majority of data is above 90 dB, with multiple points exceeding 100 dB. There is also a notable lack of symmetry, which may be the result of the fact that the mechanical siren device is located off-centre of the emergency vehicle, on the left side of the bumper.

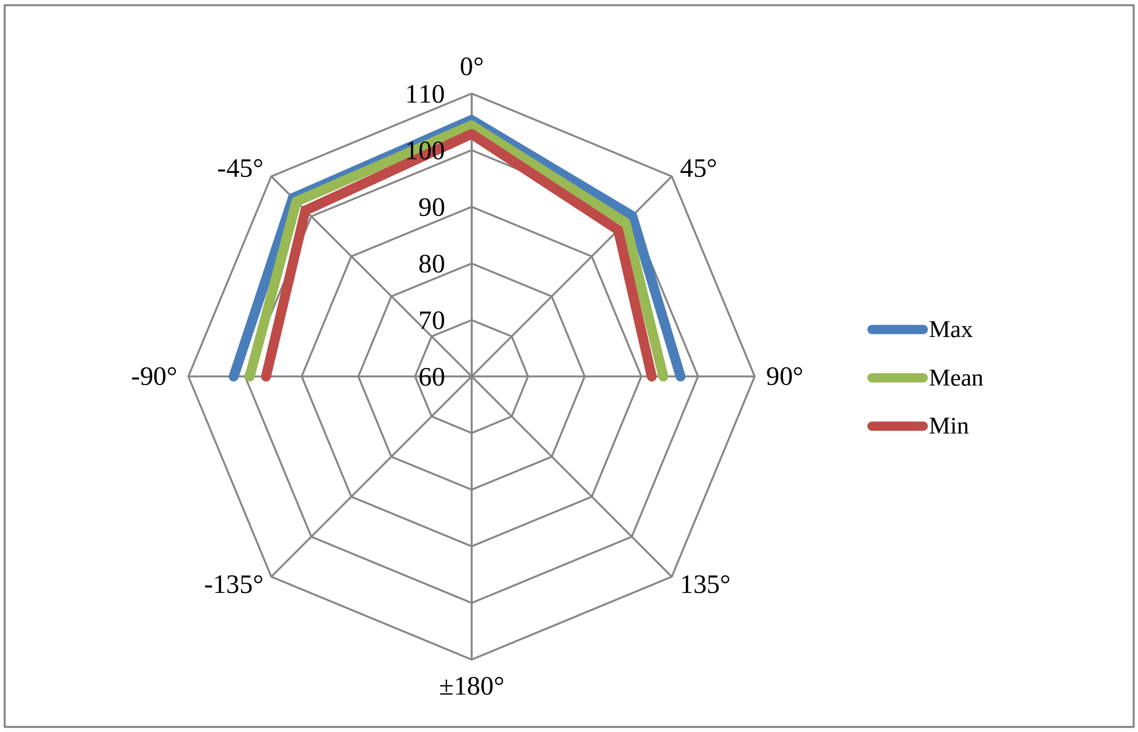

Figure 36: A-weighted Overall Time Response of the mechanical siren frontal directivity

Compared next is the directivity of the two sirens as shown in Figure 37. The data comparing the maximum and minimum outcomes are provided in Appendix C. From Figure 37, the results of the mean values for the two sirens show that the mechanical siren has significantly higher sound pressure and much better directivity covered compared to the electrical siren. The amplitude differences vary from approximately 10 dB to over 20 dB, representing substantial differences. This validates a more positive effect from the mechanical siren by providing greater radial coverage at greater sound pressure amplitudes.

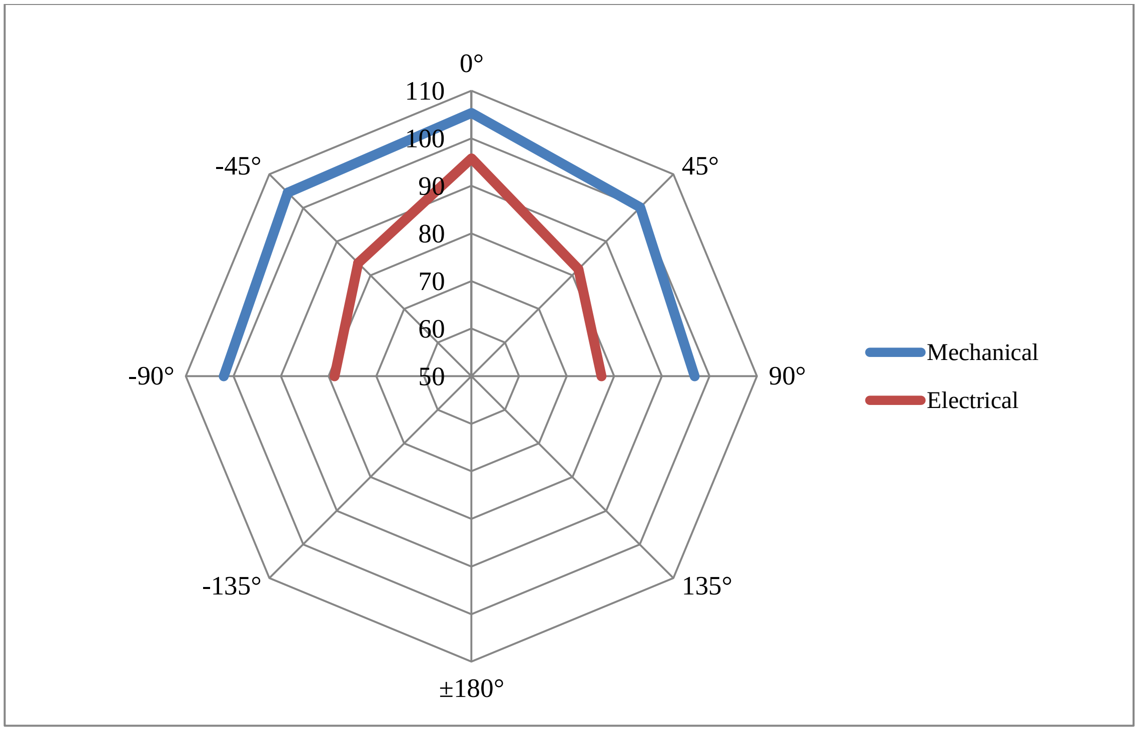

Figure 37: Mean A-Weighted Overall Time Response of the mechanical and electrical siren frontal directivity

4.2.3 Analysis of the Rumbler

The tests involving the Rumbler siren were designed to be the same as those involving the comparisons between the electrical and mechanical siren systems. Any modifications to the analysis procedure will be detailed in the discussion of the results in the following sections.

4.2.3 a) Shadow Phenomenon

The final analysis of the shadow phenomenon examined the affect that the Rumbler siren, along with the Wail and Yelp signals, had with the presence of a shadow vehicle in comparison with the standard electrical Wail siren. Shown in Figure 38 is the measured A-weighted time signals for the Yelp with Rumbler, Wail with Rumbler and Wail alone sounds. It is seen that the addition of the Rumbler to the Wail resulted in a significant increase in sound pressure over the measurement time period; it is assumed that a similar conclusion would be drawn for the Yelp siren pattern with and without the Rumbler. On average, the addition of the Rumbler resulted in a significant increase in sound pressure level of 6 dB.

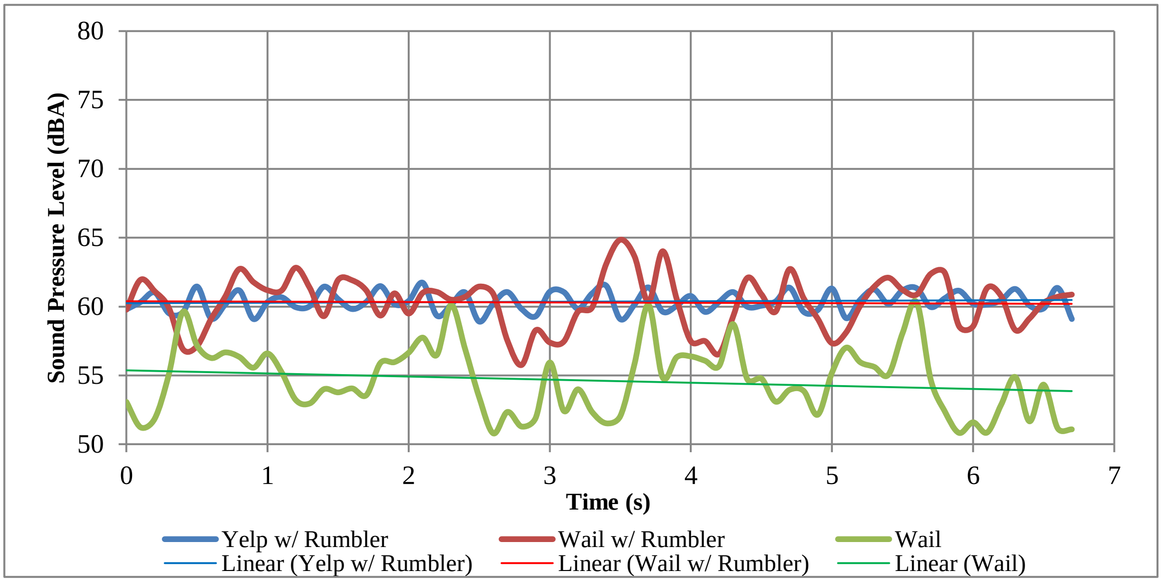

Figure 38: A-Weighted Overall Time Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren inside the receiver vehicle with the presence of the shadow vehicle with corresponding linear trend lines

Next examined was each individual siren combination, with and without the shadow vehicle present in order to investigate how each siren is affected by the presence of a shadowing vehicle. The intent of this was not to validate an affect that the presence of the shadow phenomenon has on siren detectability, as it was already determined previously, but to see what affect the addition of the Rumbler may have. Figure's 39, 40, and 41 show each siren signals data with and without the shadow vehicle. The Wail and Yelp siren, both with the addition of the Rumbler system resulted in an average attenuation of 11 dB with the presence of the shadow vehicle. The average difference between the data with and without shadow vehicle for the Wail siren only was greater than 12 dB. The addition of the Rumbler system resulted in an average increase of 5 dB among the data. The conclusion here is that the addition of the Rumbler resulted in an increased sound output, regardless of whether a shadow vehicle was present. As such, having a Rumbler siren in combination with the Wail or Yelp signal will help overcome the shortcomings associated with the presence of a shadow vehicle.

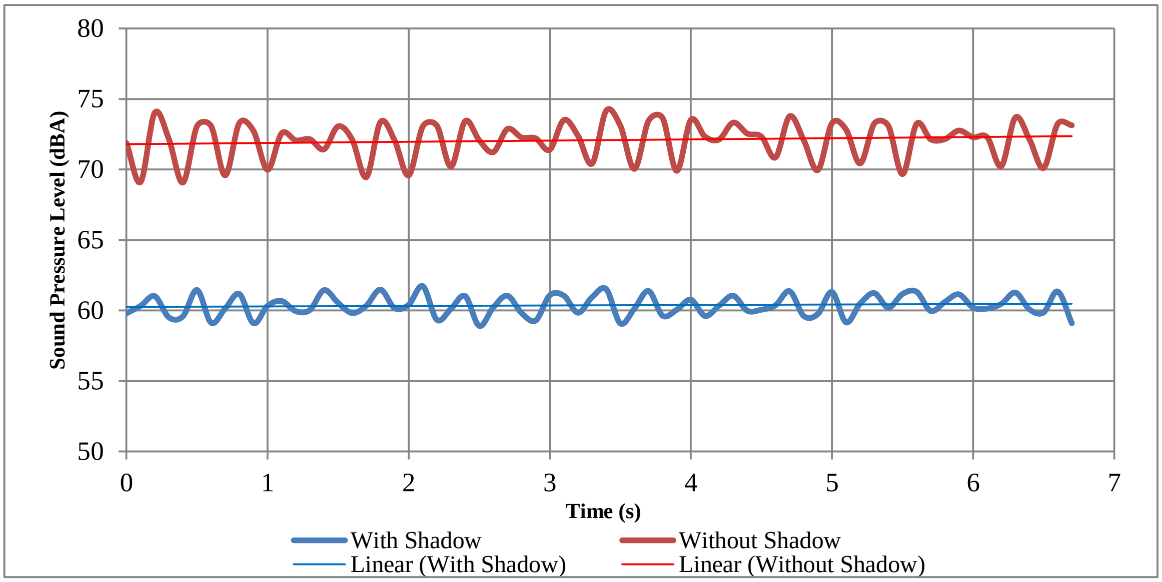

Figure 39: A-Weighted Overall Time Response of the Yelp with Rumbler siren inside the receiver vehicle with and without the presence of the shadow vehicle with corresponding linear trend lines

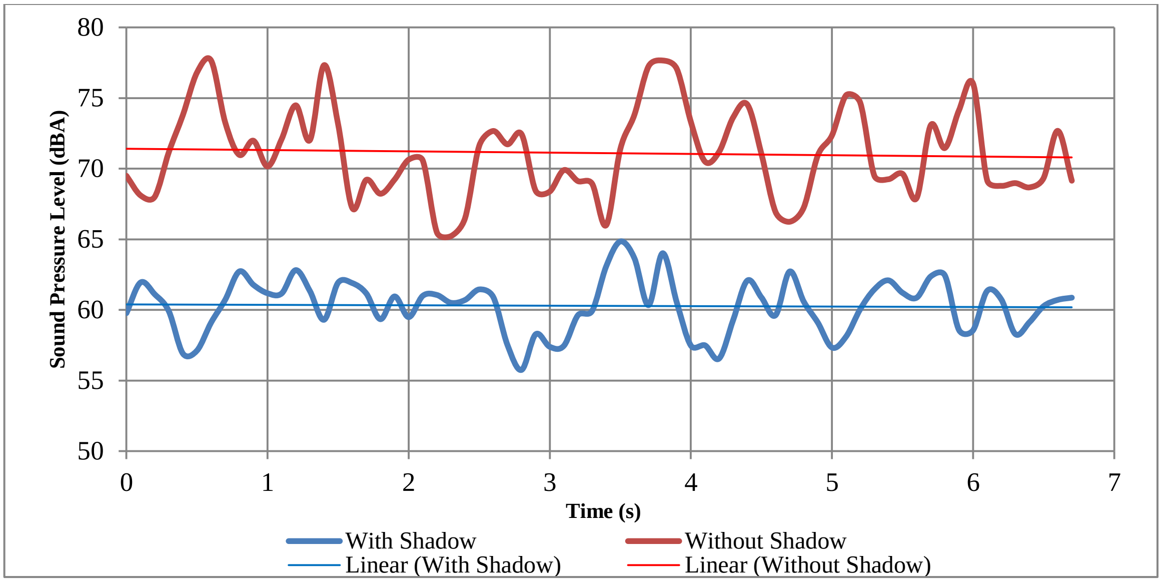

Figure 40: A-Weighted Overall Time Response of the Wail with Rumbler Siren inside the receiver vehicle with and without the presence of the shadow vehicle with corresponding linear trend lines

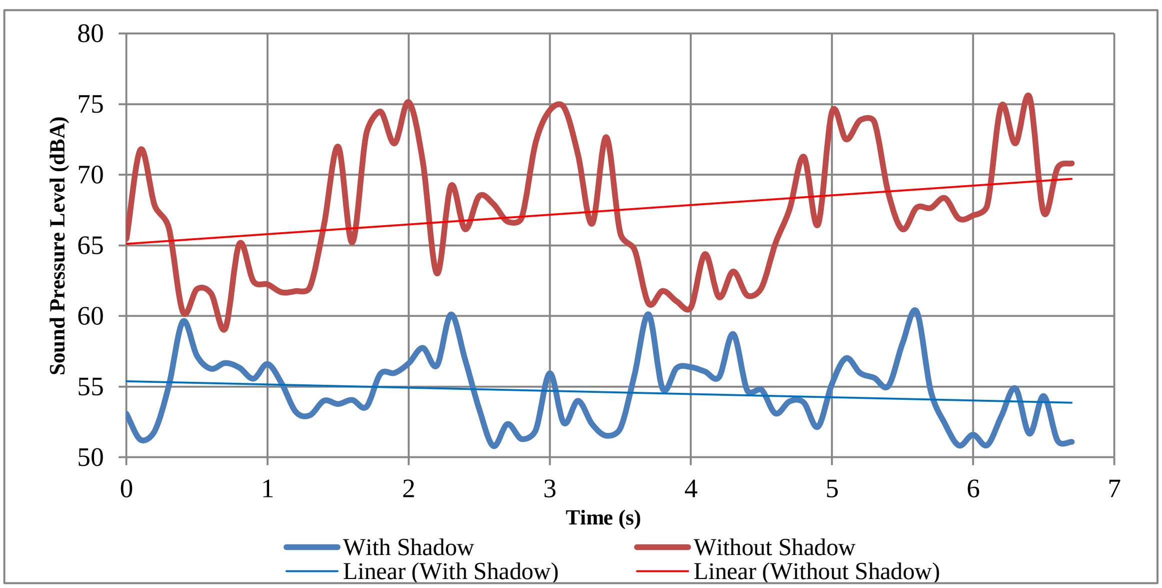

Figure 41: A-Weighted Overall Time Response of the Wail Siren inside the receiver vehicle with and without the presence of the shadow vehicle with corresponding linear trend lines

4.2.3 b) Pass-by

As was the case for with the electrical and mechanical sirens, a comparison of the three siren scenarios for the pass-by experiment is considered. As before, the data points for the three graphed lines were matched up based on the peak values from the overall time analyses. These peaks represent the point where the emergency vehicle had nearly reached the position of the receptor vehicle. In other words, it is the position where the front bumper of the emergency vehicle would just be entering the intersection. As shown in Figure 42, the addition of the Rumbler siren to the Wail and Yelp resulted in an average sound pressure level increase of over 7 dB for both siren systems.

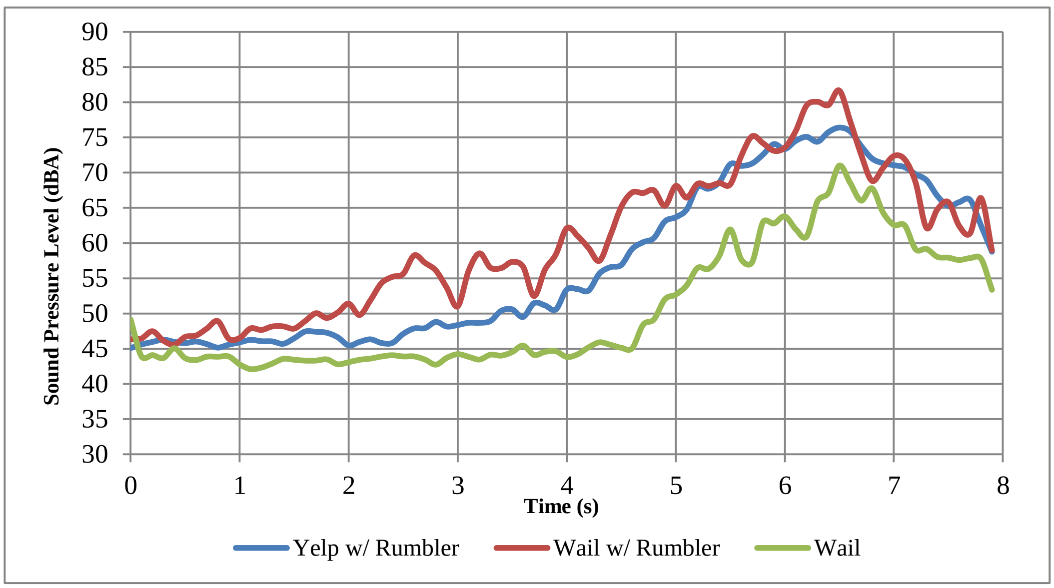

Figure 42: A-Weighted Overall Time Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren pass-by inside the receiver vehicle

4.2.3 c) Directivity

The third Rumbler analysis was to determine the frontal directivity of the siren combinations. The same general procedure that was carried out for the electrical and mechanical siren only comparison was followed with one exception; the test was conducted at two different source-to-receiver distances to investigate the Rumbler's measured sound output in relation to distance; that is, how well did it follow this inverse square law.

Figure's 43 and 44 show the mean value results for the distances of 5 m and 10 m from the centre front bumper of the police cruiser respectively. Through examination of these plots, it is observed that the addition of the Rumbler system resulted in higher sound pressure levels at all positions tested. The difference was not substantial, but is large enough such that the increase is easily perceivable.

As before, the comparison of the maximum and minimum data for these siren cases is included in Appendix C. However, examination of those figures showed that the maximum and minimum values from the Yelp siren differed by only a few decibels; whereas, the Wail and Wail with Rumbler signals produced average differences of over 10 dB between the maximum and minimum values. These differences were due to the characteristics of these siren signals, as was the case with the mechanical and electrical siren comparison on the fire truck.

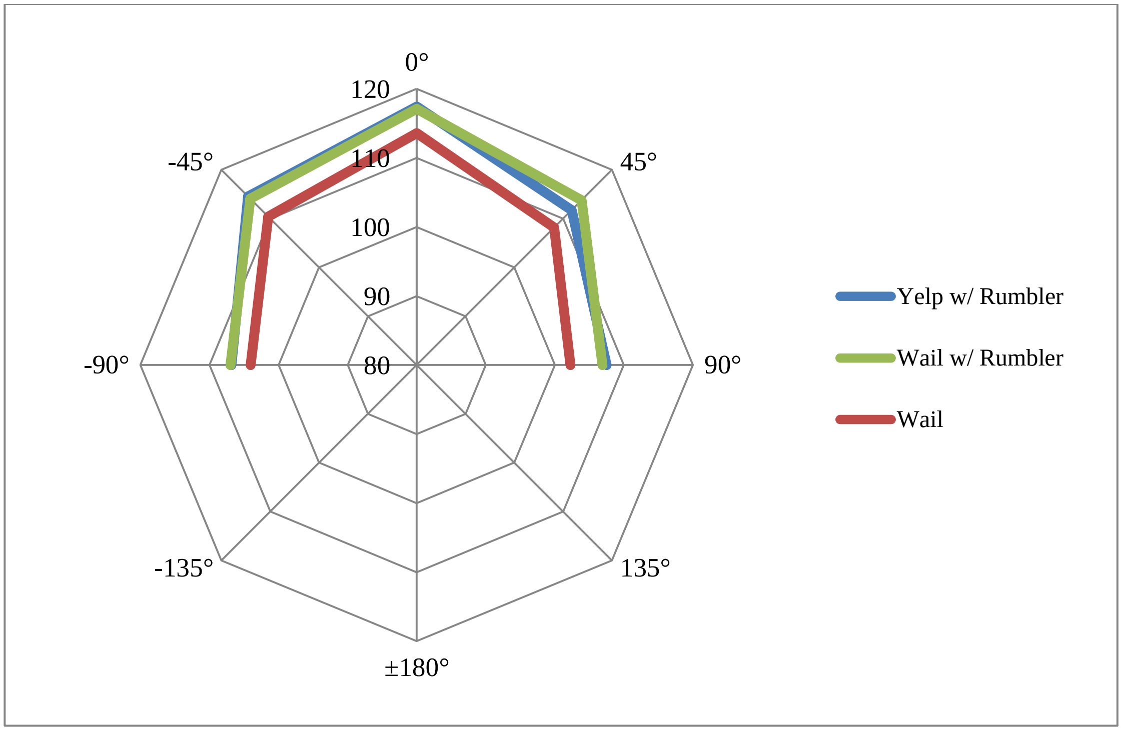

Figure 43: Mean A-Weighted Overall Time Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren frontal directivity at a measurement distance of 5 m

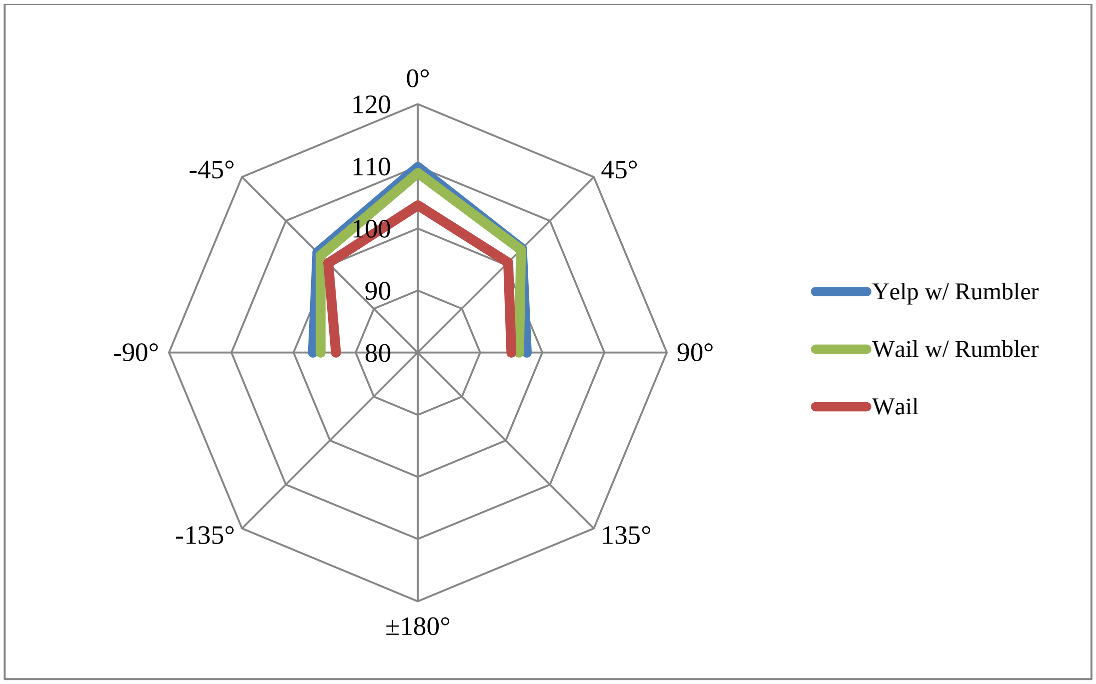

Figure 44: Mean A-Weighted Overall Time Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren frontal directivity at a measurement distance of 10 m

Also provided in Appendix C is the comparison of each siren at the two measurement distances, to compliment the results shown in Figure's 43 and 44. In theory, a signal's sound pressure level should diminish by 6 dB when the distance between the source and receiver is doubled (inverse square law). However, the average difference in sound pressure level between the two distances was approximately 10 dB for the three sirens measured. This increase was likely due to the absorption and reflection characteristics of the testing environment, possibility of the measurements occurring in the acoustic near field (varying echo effects) [4], as well as experimental errors involved in the testing, the latter of which is addressed in the next chapter.

4.3 Psychoacoustic Analysis using Objective Sound Quality Metrics and Subjective Testing

The second fundamental focus for the analysis of the acquired data was a psychoacoustic analysis using both the objective sound quality metric of loudness as well as subjective jury evaluations. The objective evaluation involved processing the recorded data using the B&K PULSE Reflex software. The purpose of examining this sound quality metric was to act as a reference for the test data obtained during the subjective testing. In theory, the results of a properly executed subjective analysis should coincide with the results from the processed sound quality data using the post-processing software.

4.3.1 Sound Quality Metrics

The sound quality analysis of the measured data involved the calculation of loudness. The loudness metric is the most fundamental of the sound quality metrics, and one that many other sound quality metrics are based on. Loudness has been shown to have much better correlation to human perception than simple A-weighting of the measured data. The calculation of loudness for the electrical and mechanical sirens is presented first. Table 4 illustrates the loudness results for the cases with and without the shadow vehicle present. It was found that the loudness was nearly doubled when the shadow vehicle was absent which corresponds to a notable increase.

Table 4: Overall Time Average of Loudness (sone) Response of the electrical and mechanical siren inside the receiver vehicle with and without the presence of the shadow vehicle

Siren	**Condition**	
	With Shadow	Without Shadow
Electrical	11.4	20.7
Mechanical	12.8	23.9

The second sound quality comparison was for the perceived loudness for the pass-by experiments. The loudness here is given with respect to time, as the loudness was not constant due to the moving emergency vehicle. Based on Figure 45, the mechanical siren system has more loudness than the electrical siren, which would also correspond to better perceptibility. The presented data also shows a noticeable increase in loudness for the data that includes the effect of the air horn.

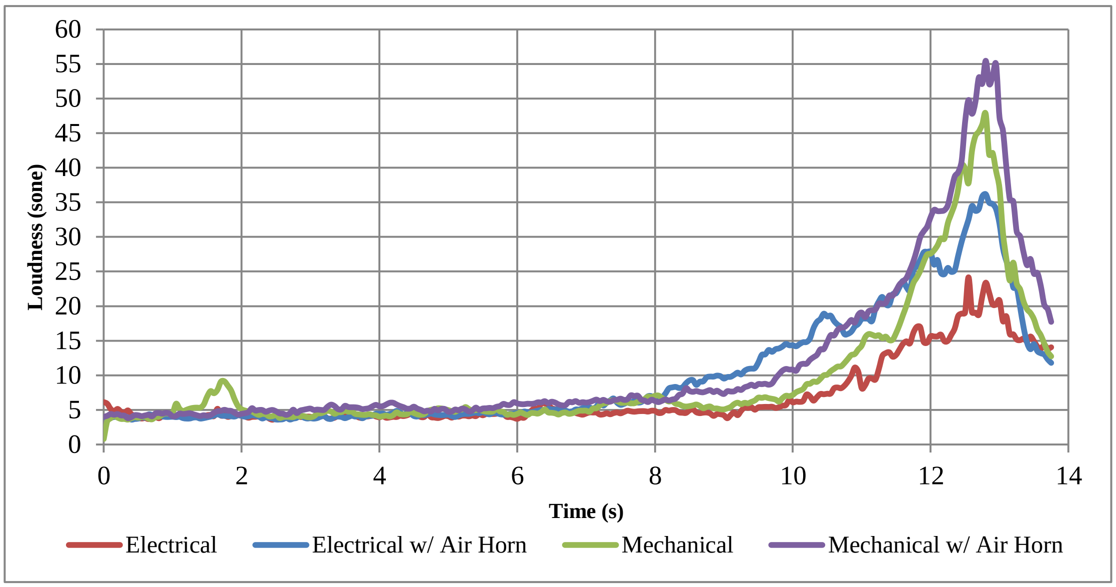

Figure 45: Loudness Overall Time Response of the electrical and mechanical siren pass-by with and without the air horn inside the receiver vehicle

As for the case of the mechanical and electrical siren comparison, sound quality metrics were also used for the evaluation of the Rumbler siren. Table 5 illustrates the loudness results for the shadow phenomenon data for the three siren cases as presented previously. Again, the consensus is that the presence of the shadow vehicle results in a loudness value that is nearly half as much as for the case with no shadow vehicle. Also important to note, was that the absence of the Rumbler results in a significant decrease in the calculated loudness.

Table 5: Overall Time of Average Loudness (sone) Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren inside the receiver vehicle with and without the presence of the shadow vehicle

Siren	Condition	
	With Shadow	Without Shadow
Yelp with Rumbler	10.9	19.7
Wail with Rumbler	10.6	20.2
Wail	7.2	14.3

Figure 46 illustrates the loudness results from the pass-by analysis tests, which compares the loudness of the three siren cases. The same scale that was used for Figure 45 was also used here so that the results can be directly compared. Between the three sirens, the addition of the Rumbler has a significant impact. Another observation made is that there is a noticeable difference between the electrical siren from the fire truck data in Figure 45 and the standalone Wail siren in Figure 46. Both sirens are essentially the same system with the only difference being two different speakers. The loudness of the electrical siren on the fire truck was determined to be 23.7 sones at its peak while the Wail siren on the police cruiser was only 13.3 sones. This difference of over 10 sones is attributed to the noise from the emergency vehicle itself. That is, the fire truck itself is a louder vehicle when being driven. This same relationship is observed for the shadow phenomenon loudness analysis.

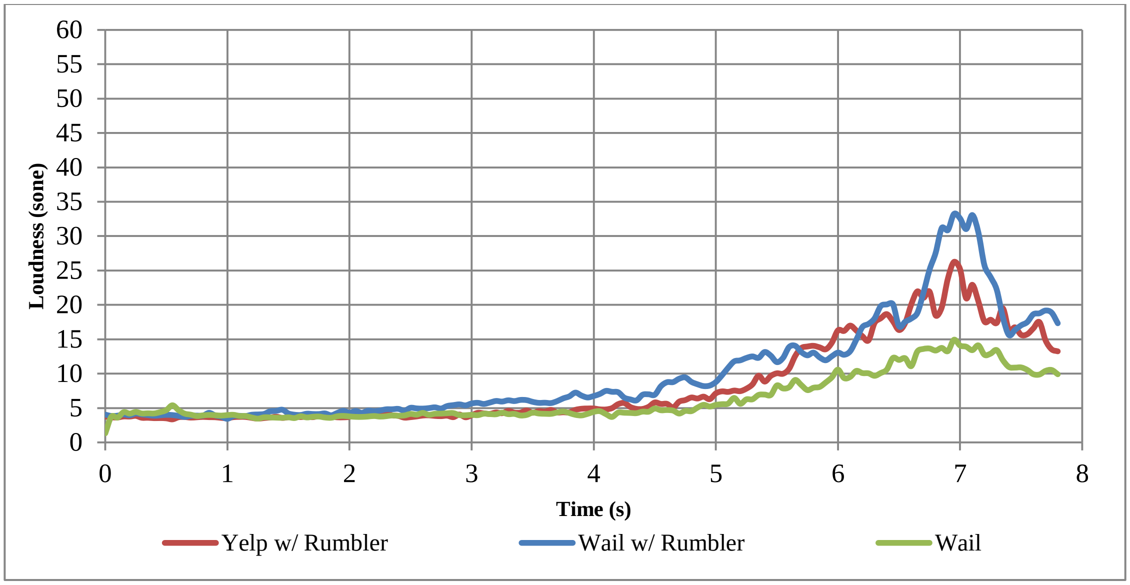

Figure 46: Loudness (sone) Overall Time Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler siren pass-by with the air horn inside the receiver vehicle

As stated earlier, the loudness evaluation was conducted to be a guide for the design of the jury test. It also served as a comparison between the objective and subjective results. Both the sound quality analysis and the design of the subjective tests were such that direct comparisons would be possible with the hope that they would also both reach the same conclusions.

4.3.2 Subjective Testing

The primary purpose of the jury evaluation is to support and validate the conclusions taken from the experimental testing results. The test was designed to determine and rank the perceived loudness of the siren signals. Being a subjective test, an absolute loudness unit is not possible, only a relative ranking. As such, the rankings and repeatability score taken from the juror results was recorded by the software and used to judge the performance. For the jurors who participated in the study, an average repeatability of 89.3% was calculated. The repeatability score for each juror is given in Table 6. In addition to examining the repeatability scores, the juror answers to some control questions were monitored to ensure the juror was performing the test properly and that there was no fatigue. It is important to note that none of the jurors were given a hearing test prior to the evaluation. Although it is assumed that a person within the age range of 18 to 30 has good hearing, it would have been worthwhile to determine if any of the participants suffered from any degree of hearing loss.

Table 6: Overall jury repeatability scores

Juror ID	No. of Inverted Repeats	No. of Consistent Votes	% Repeatable
J0001	16	16	100.0
J0002	16	15	93.8
J0003	16	14	87.5
J0004	16	13	81.2
J0005	16	15	93.8
J0006	16	12	75.0
J0007	16	11	68.8
J0008	16	13	81.2
J0009	16	16	100.0
J0010	16	15	93.8
J0011	16	14	87.5
J0012	16	13	81.2
J0013	16	14	87.5
J0014	16	13	81.2
J0015	16	16	100.0
J0016	16	14	87.5
J0017	16	15	93.8
J0018	16	13	81.2
J0019	16	15	93.8
J0020	16	15	93.8
J0021	16	16	100.0
J0022	16	16	100.0
J0023	16	15	93.8
J0024	16	15	93.8
J0025	16	11	68.8
J0026	16	16	100.0
J0027	16	15	93.8
J0028	16	13	81.2
J0029	16	13	81.2
J0030	16	16	100.0
J0031	16	16	100.0
J0032	16	13	81.2
Average		14.3	**89.3**

Given in Table 7 are the subjective results comparing the electrical and mechanical siren with and without the presence of the shadow vehicle. The results show that, on average, 99.2% of the jurors selected the scenario without the shadow vehicle present as being louder. It is thought that perhaps the very small percentage of participants (one person for the mechanical siren pair of the test only) that selected the opposite was likely attributed to the background traffic noise from the simulator software. In addition to the comparison of with and without the shadow vehicle, the electrical and mechanical signals, both with the shadow vehicle present, were paired against each other. It was found that 95.3% of participants perceived the mechanical siren as being louder compared to the electrical siren.

Table 7: Jury Response of the Mechanical and Electrical Siren inside the receiver vehicle with and without the presence of the shadow vehicle

Siren	Scenario	
	With Shadow Vehicle (%)	No Shadow Vehicle (%)
Electrical	0.0	100.0
Mechanical	1.6	98.4
Average Selection of No Shadow Vehicle		99.2

The next results are for the comparison of the electrical and mechanical for the pass-by analysis, which also includes the air horn siren. Figure 47 shows the results for this subjective analysis. Examination of this data shows a clear preference of the mechanical siren over the electrical. The air horn system was also preferred by an average of 96.1% of the jurors between both the electrical and mechanical siren systems. Comparing the two siren systems with the addition of the air horn system resulted in the jurors preferring the mechanical siren with the air horn 98.4% of the time.

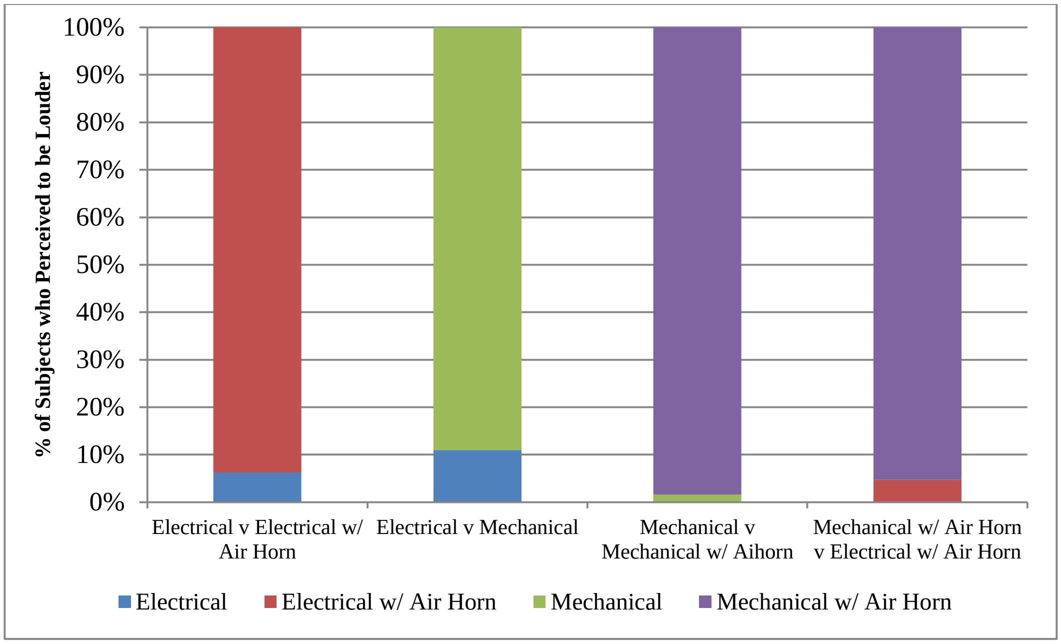

Figure 47: Jury Response of the Mechanical and Electrical Siren pass-by with and without the air horn inside the receiver vehicle

Figure 48 is a plot that illustrates the repeatability of the pass-by evaluation for the mechanical and electrical siren analysis. It was determined that the repeatability of the pairs involving the addition of the air horn on average scored over 95%, while the repeatability of the standalone comparison of the electrical and mechanical comparison scored 90.6%. These are very strong numbers in support of the mechanical siren, with or without the addition of the air horn.

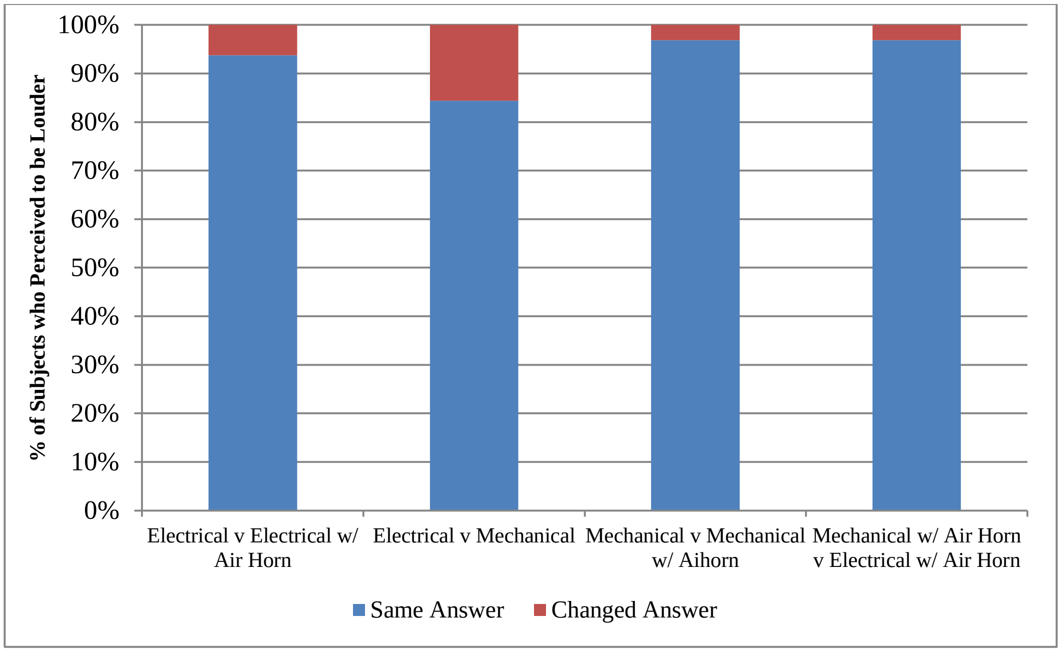

Figure 48: Jury Repeatability of the Mechanical and Electrical Siren pass-by with and without the air horn inside the receiver vehicle

The above analysis was repeated for the siren signals with the addition of the Rumbler siren. The results with the Rumbler under the conditions with and without the shadow vehicle are given in Table 8. It is shown that 99.5% of the jurors identified the signal without the shadow vehicle present as being the perceived louder siren scenario. Again, the small percentage of participants that identified the signal with the shadow vehicle present as being perceived as louder was likely attributed to the background traffic noise from the simulator software.

Table 8: Jury Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler Siren inside the receiver vehicle with and without the presence of the shadow vehicle

Siren	Scenario	
	With Shadow Vehicle (%)	No Shadow Vehicle (%)
Wail	1.6	98.4
Wail w/ Rumbler	0.0	100.0
Yelp w/ Rumbler	0.0	100.0
Average Selection of No Shadow Vehicle		99.5

In addition to comparing the signals with and without the presence of the shadow vehicle, a comparison of the signals (with the shadow vehicle present) against one another was also investigated. From Figure 49, it is observed that the jurors consistently chose the addition of the Rumbler over the case without 97.7% of the time. There was also a preference of the Yelp over the Wail siren.

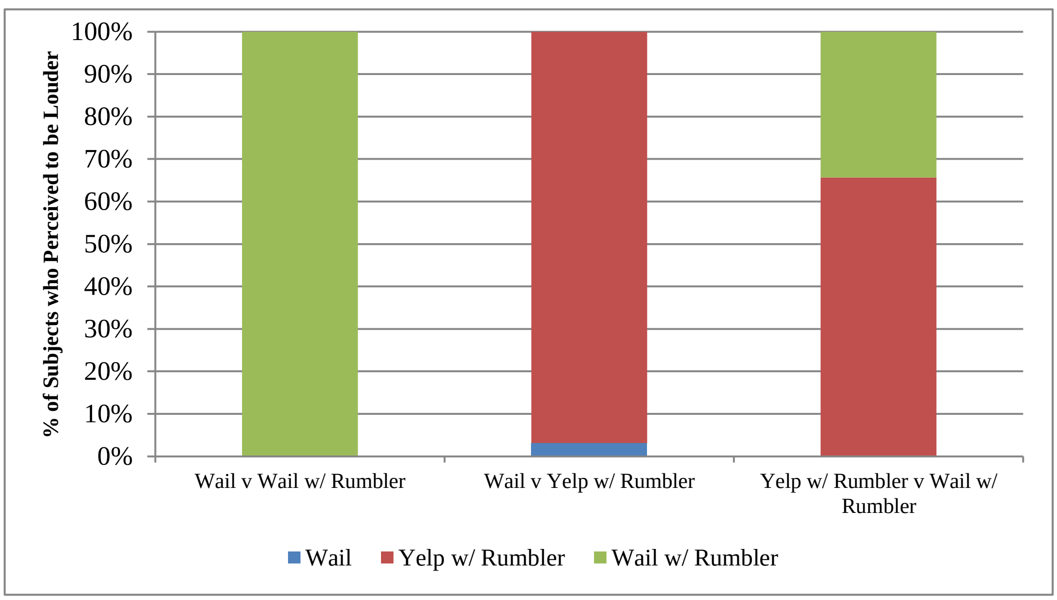

Figure 49: Jury Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler Siren inside the receiver vehicle with the presence of the shadow vehicle

Figure 50 shows the results from the pass-by tests, which include the Rumbler. Similar to the shadow phenomenon comparison, the sirens that included the Rumbler system are preferred by 91.4% of the participants. However, comparing the Yelp and Wail signals, both with the Rumbler addition, show an inverse data trend compared to the shadow test results. The Wail with the Rumbler is preferred by 76.6% of the jurors. This change in pattern can be likely attributed to the characteristics of the sirens during the recording exercise. During the shadow vehicle testing, the emergency vehicle was immobile, and as a result, the sound at the receiver was steady. On the other hand, during the pass-by test, the sirens sounds increase in intensity before they reached a peak level just prior to passing the receptor vehicle. Based on reinvestigation of the recorded sounds, it was found that the Wail siren was at its peak amplitude at the immediate pass-by position. As a result, it was often perceived as being louder over the Yelp signal. Unfortunately repeated measurements were not acquired which would have aided in the comparison between the Yelp and Wail signals. However, the results still confirmed the effectiveness and preference of the Rumbler siren.

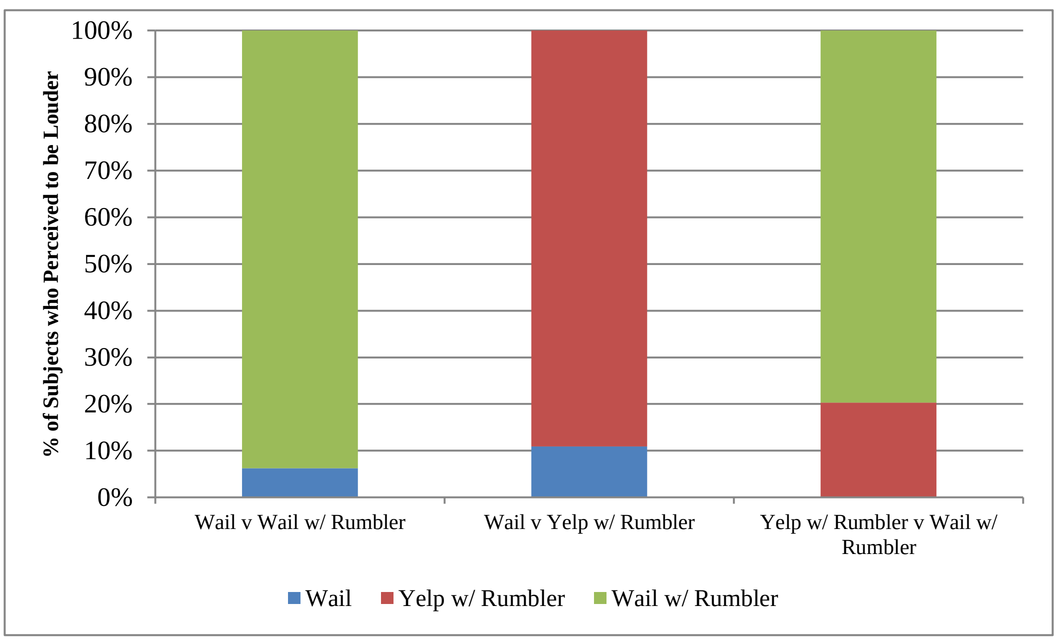

Figure 50: Jury Response of the Wail alone, Wail with Rumbler, and Yelp with Rumbler Siren pass-by inside the receiver vehicle

Figure 51 illustrates the repeatability of the pass-by siren tests. These results confirm the difficultly that some of the participants experienced in their comparison between the Wail with Rumbler versus the Yelp with Rumbler sirens as nearly 20% changed their answer when the pair was re-presented to them.

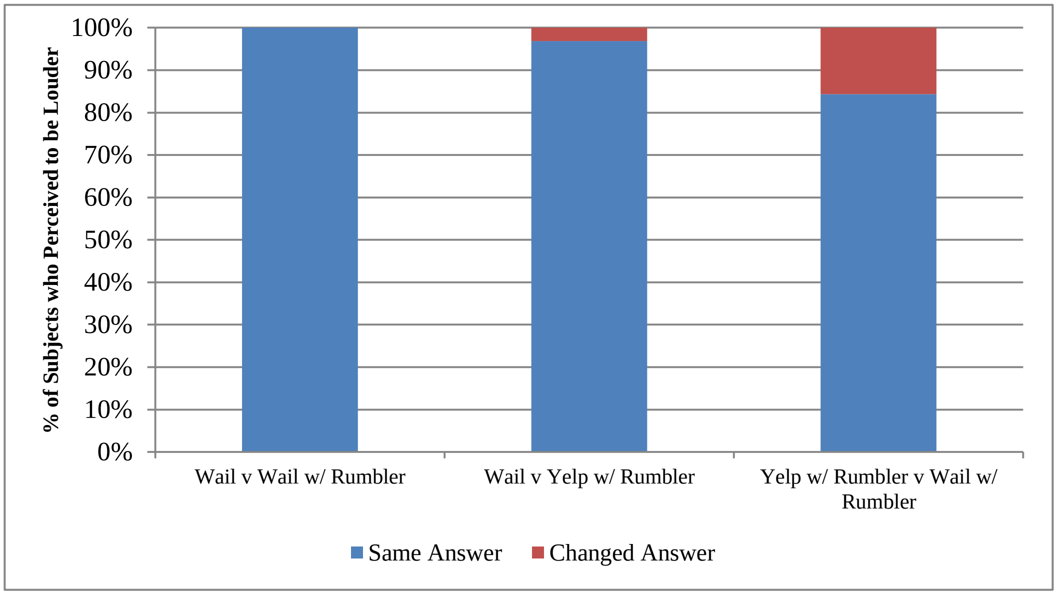

Figure 51: Jury Repeatability of the Wail alone, Wail with Rumbler, and Yelp with Rumbler Siren pass-by inside the receiver vehicle

In addition to the tests already detailed, a further investigation into objective sound quality metrics was carried out to aid in the assessment of the siren signals. A particular sound characteristic common to siren sounds is modulation. To quantify this characteristic, the two sound quality metrics of modulation strength and fluctuation strength are often used. These modulation metrics are used to quantify a sound's annoyance, alerting nature, and often-perceived urgency. It is important to note that the maximum modulation amplitudes are at frequencies of 70 Hz and 4 Hz for the roughness and fluctuation strength respectively [13]; as such, only roughness was examined for the Yelp and Wail signals, as it was the more accurate representation. The results of the analysis are provided in Table 9. With the understanding that a rough signal is generally perceived as more annoying and alerting, these results validate the preference of the Yelp over the Wail by over a factor of two.

Table 9: Roughness (asper) Response of the Yelp with Rumbler and Wail with Rumbler Siren inside the receiver vehicle with the presence of the shadow vehicle

Parameter	Roughness [asper]			
Siren	Yelp with Rumbler		Wail with Rumbler	
Signal	Left Ear	Right Ear	Left Ear	Right Ear
Level	1.652	1.537	0.618	0.794
Average	**1.594**		**0.706**	

CHAPTER 5

DISCUSSION

5.1 Summary

5.1.1 Mechanical v. Electrical System Comparison and Analysis with the Rumbler

The first focus for this investigation was the comparison of the noise outcomes for traditional mechanical siren system to the newer electrical siren system. As discussed, this acoustical comparison was composed of three tests: shadow phenomenon, pass-by, and frontal directivity. The results from the frequency analysis of shadow testing led to the initial conclusion that electrical siren's acoustic characteristics were more capable of overcoming the attenuation characteristics of the intervening vehicle barrier. The overall time data and A-weighting analyses, however, produced results in favour of the mechanical siren as being a more effective warning system. With this in mind, it is important to note a few key points. All those present during the experiment considered the mechanical siren significantly louder as well as more alarming and alerting. Second, the mechanical siren also proved to be more effective in the absence of the barrier, which suggests that the mechanical siren may be more effective overall. This was further validated in the remaining two tests.

The second test conducted was the pass-by experiment, which also involved the testing of the air horn system. Based on the analysis, the mechanical siren outperformed the electrical siren with and without the addition of the air horn system. The period where the siren data was examined with the most stress was the few seconds before the acoustic maximum, which in turn was observed at the position when the siren signal reached the front of the receptor. This position is a critical segment in a traffic scenario as it is just before the emergency vehicle reached the perpendicular traffic. This part of the study also demonstrated that the addition of the air horn was also effective and should be incorporated with the other sirens to help warn and clear a traffic intersection.

The next investigation involving the electrical and mechanical system comparison was the measurement of frontal directivity. It was concluded that the traditional mechanical siren was significantly louder and had a greater spread of acoustic energy radiation compared to the newer electrical siren design. In other words, the data showed that the acoustic characteristics of the mechanical siren system produced higher and more consistent radial sound pressure levels in the frontal direction.

With this conclusion in mind, it was still important to note a point of interest observed during the investigation. First, the mechanical siren was slightly more effective towards the left side of the fire truck due to its mounting location on the left side of the front bumper. However, this should not be considered a hindrance given that when a fire truck is approaching an intersection, the further off-axis that vehicles are positioned toward the left of the emergency vehicle and nearer to the mounting location of the siren will aid in reducing the impacts of the higher source-to-receiver distance.

Next, the above experiments were repeated with the inclusion of the Rumbler siren system. This analysis involved the same three experimental tests that were conducted for the mechanical and electrical comparison. In regards to having the shadow vehicle present, two major conclusions were reached. The first was that the addition of the Rumbler siren resulted in a higher sound pressure level when the shadowing vehicle was present compared to the system without the Rumbler. The second conclusion was that among the individual siren comparisons, which considered the differences with and without the shadow vehicle present, there was a noticeably smaller gap between the sound levels when the Rumbler system was active. The effectiveness of the Rumbler is attributed to its low frequency characteristics, which resulted in higher sound penetration through the structure of the vehicles.

The pass-by tests resulted in the same general conclusion that the Rumbler resulted in a more effective audible warning system. The addition of the Rumbler siren resulted in a perceivable difference in sound output over a period of multiple seconds before the emergency vehicle reached the receptor vehicle's position. This was significant as an additional one or two seconds can be crucial in the case of avoiding an emergency vehicle collision.

The final test conducted was the directivity measurements. These considered two different test distances of 5 and 10 m from the centre front bumper of the police cruiser. Again, the first observation from this analysis was an increased sound pressure at all positions with the addition of the Rumbler system. Next considered were the acoustical characteristics for each of the siren cases. It was found that the average difference between the maximum and minimum values was 4, 11, and 16 dB for the Yelp with the Rumbler, Wail with the Rumbler, and the standalone Wail signals respectively. The difference between the two siren systems with the Rumbler was as expected, again due to the low frequency modulating characteristics of this type of signal; however, the difference between the Wail with and without the addition of the Rumbler siren was significant and was a deciding factor in terms of validating the effectiveness of the

Rumbler siren. The final outcome of the directionality assessment was the differences in sound level observed between the two measurement distances. In theory, the difference in sound pressure level should be 6 dB for an ideal source when the distance between the source and receiver is doubled. The changes in the SPL in the study were generally around 10 dB. This may be attributed to a combination of the effects of absorption and reflection present in the testing environment, errors involved, as well as the possibility that the measurements at these distances were still in the near field acoustic region. In any case, care should be taken in future work to not acquire noise measurement of this siren at too near a distance.

5.1.2 Psychoacoustic Analysis using Objective Sound Quality Metrics and Subjective Testing

The investigation of siren effectiveness using sound quality metrics in combination with subjective jury tests was used to validate and expand upon the results from the experimental noise tests. The purpose of these analyses focused on four points of interest: further examination of the shadow phenomenon, comparison of the electrical versus the mechanical siren systems, validation of the simultaneous use of the air horn, and investigation (leading to the validation) of the Rumbler low frequency siren system. Many of these criteria are intertwined and overlap with one another. The following discussion is in relation to the results gathered from the psychoacoustic part of the research.

The objective part of the study concluded that the shadow phenomenon was a significant factor in the effectiveness of emergency vehicle siren systems. It was unclear whether the presence of a blocking vehicle would result in a perceivable change in loudness among the entire sample population. Examining the results from the entire portion of the jury evaluation (the electrical versus mechanical comparison as well as the analysis of the Rumbler system), it was determined that 99.4% of the participants selected the signal in which the shadow vehicle was absent as being perceived as louder. The remaining 0.6% of participants that selected otherwise can likely be attributed ambient traffic noise during the simulation of the signal in which the shadow vehicle was present, thus falsely presenting itself as louder. In any case, the data overwhelmingly concluded the adverse acoustic effects resulting from the presence of a blocking vehicle on the sound output of all the siren systems.

The results of the processed objective sound quality results showed that the mechanical siren was twice as loud as the electrical siren at all data points. The outcome from the subjective jury evaluation concluded that the mechanical siren was perceived to have greater loudness by 95.3% of the jurors during the shadow vehicle comparison (shadow vehicle was present during signal playback). The results from the subjective pass-by tests resulted in 89.1% of the jurors indicating that the mechanical siren was the louder option. This conclusion is further reinforced for the case having the addition of the air horn.

The results from the addition of the air horn siren in conjunction with the other sirens during the pass-by tests conclude that this combination significantly increased the loudness of the warning system, whether it was the mechanical or electrical system. At the peak levels, the addition of the air horn system produced a loudness of 55.5 and 36.2 sones inside the receiver car for the mechanical and electrical siren systems, respectively. The jury test paired the mechanical and electrical siren alone against the same system with the addition of the air horn, i.e. mechanical versus mechanical with the air horn addition. The participants selected the signal with the addition of the air horn 98.4% and 93.8% for the mechanical and electrical system comparisons respectively, as being the louder option. The final comparison consisted of both siren systems with the air horn paired with one another; it was determined that the participants perceived the mechanical siren with the air horn to be louder 95.3% of the time. This is a significant increase from 89.1%, which led to the validation of the air horn siren's effectiveness.

The next part of the study repeated the above analysis, only now with the addition of the Rumbler siren system. The processed data from the early non-psychoacoustic discussions preliminarily demonstrated the positive effectiveness of the Rumbler, but it was also evident that further work was required before any concrete conclusions could be reached. The psychoacoustic analysis using the Reflex post-processing software showed that the addition of the Rumbler siren increased the loudness on average by factors of 1.5 and 2 for the shadow and pass-by test respectively. Although the subjective jury test was not capable of calculating a numerical value in terms of an increase in loudness, a preference among the juror's was determined. The results from the shadow test indicated that 97.7% of the participants perceived the Rumbler sounds to be louder. Similar results were found for the pass-by pairs, with 91.4% of the jurors perceiving the addition of the Rumbler system to be louder. Combining the results yielded preference for the Rumbler at 94.6%. These results incontrovertibly verify the overall effectiveness of the Rumbler siren in conjunction with the standard electrical siren system.

A final observation made during the analysis of the Rumbler siren system analysis was the mixed preference between the Wail and Yelp siren modes. The participants perceived the Yelp signal 73.4% over the Wail for the shadow vehicle testing but perceived the Wail signal 76.6% over the Yelp for the pass-by testing. Previous mention of this discrepancy in Chapter 4 briefly discussed that the reason for these inconsistencies were attributed to the peak level of the Wail siren being recorded as the emergency vehicle pass-by noise peaked. In essence, the highest sound output of the varying Wail siren was unintentionally recorded resulting in a louder signal compared to the recorded Yelp. It should be noted that the Yelp signal was preferred during the shadow test, during which several cycling periods of each stationary siren were recorded and compared, thus overcoming the above noted anomaly. A final analysis was conducted which examined the roughness characteristics of the two siren signals. The results confirmed the Yelp siren to having a higher roughness, which was more than double the Wail's roughness. This metric can be related to other subjective preferences such as perceived urgency and annoyance, which are all favourable characteristics of an effective emergency siren.

5.2 Limitations

While this study examined multiple siren systems as well as several factors of application pertaining to their effectiveness, there are still limitations to how the study was conducted. The first and most significant limitation was the modification from the acoustic SAE testing practice for siren noise [18].

A first deviation was the testing environment that was used to collect the noise data. The SAE recommendation suggests the testing take place in an anechoic chamber. This would require a very large chamber; one which is larger than the chamber located at the University of Windsor NVH lab. This would also preclude any of the pass-by tests or test requiring two vehicles. Instead, the test environment was an outdoor setting, chosen to best achieve free-field acoustic conditions. A second modification to the test procedure was the omission of the siren warm-up period, of approximately 10 min. The reason for not performing this operation is that it would cause disturbance to nearby populated areas. These include residential neighbourhoods as well as commercial properties.

The SAE guide also has recommendations for siren mounting height, specified distance from the source to the receiver, as well as specifications for the number and type of measurements. The mounting height was not followed for the sole reason that all of the sirens tested were mounted to the emergency vehicle and so the height could not be changed. The distances between the source and the receiver were also modified significantly to instead accurately represent the designed traffic scenario simulation. It was felt this this was a reasonable deviation given the application of the subjective evaluations.

Not related to the recommended testing document, another limitation in this study was the use of only one sample receptor vehicle for the shadow, pass-by, and noise reduction tests. The decision of using the 2010 Ford Focus was primarily due to ease of access as well as it was an accurate representation of a typical modern passenger vehicle. However, the use of only a single vehicle meant that the data was not representative across all vehicle sizes and types. This can have an impact for the consideration of more luxury style vehicles, which are designed and built with the highest possible noise attenuation characteristics. While this increased attenuation is a positive for the driving experience of the occupants, it is a direct hindrance to the perception of emergency sirens. Not including testing of such luxury style vehicles may be viewed as a shortcoming of this study. However, the conclusions that have been made are still generally applicable in the sense that luxury vehicles can still be impacted by the presence of a blocking shadow vehicle; however, the level of impact of this was not investigated.

Another limitation in this study was that it focused mostly on the sound quality metric of loudness. While loudness is indeed the most relative and informing sound quality metric, there are other acoustical characteristics that are of interest, namely: perceived urgency, harshness, alertness, and pleasantness. However, these metrics are usually customized for a very specific application and not readily available. In any case, it was still appropriate to use the loudness metric to design and validate the subjective tests.

A drawback of the subjective study was the limited age range. Participants were selected from the range of 18 to 30 years of age. This is normal unless the jurors above the age of 30 have recently completed a hearing test resulting in a normal outcome. The concern with the limited age range is that it only represented a small percentage of the driver’s on the road. Young drivers of the ages 16 and 17 as well as drivers over the age of 30 are not represented in this study.

A final limitation of the work is the fact that the jury evaluation was performed using a simulated scenario in a partial vehicle buck. An improvement would be to use a full vehicle simulator (FVS), which would add more context and better represent the simulated scenarios and traffic conditions. However, the ideal subjective test would require the participant on a traffic road and actual emergency vehicles used; this form of testing would represent the conditions being investigated more accurately.

5.3 Uncertainty Analysis

The uncertainty involved in this study can be attributed to three components. The first was the error involved in the actual conducting of the experiments. This was broken up into human error and error due to the background noise. The human error may have been due to errors in measuring distances in the experimental setup as well as any noise interference with the recordings, such as breathing within the vehicle next to the HATS.

The background noise present was also a potential factor, which may have affected the recorded data. This would have included nearby traffic noise, as well as aircraft noise. To the best of the researcher's ability, recordings were only taken and subsequently chosen for processing where the quality of the acquisition appeared to be satisfactory. During the data processing, the recordings were examined in great depth in order to ensure that any noise interference was isolated from the processed data through slicing techniques. Once the processing of the data was complete, the values were again examined and any inconsistencies among the data were addressed and labeled accordingly.

Another potential cause of uncertainty during the post-processing of the data was how the left and right ears of the HATS were combined. At present, several methods exist for the combining of binaural sound recordings. It was decided that the method chosen for this study was logarithmic addition for the recorded signal from the left and the right ears, using Equation 6. Logarithmically adding the signals resulted in an average increase in sound pressure level of 3 dB. Generally, a change of 3 dB would noticeably affect the results; however, since the signals were being compared against one another and not to some standard or reference sound level, an increase of 3 dB was viewed as insignificant.

It should be noted that some accepted practices of binaural addition could have resulted in increases of level as much as 5 or 6 dB.

In relation to the subjective testing, an uncertainty always exists where human participants are used for subjective evaluation of data. This testing was carried out in accordance with common and accepted jury evaluation guidelines. More than 30 participants were used for this study, which is above the minimum recommendation of 20 participants. The average repeatability among the participants was approximately 89.3%, which is a good result considering half of the evaluation consisted of repeated pairs. The high repeatability also validated the test design and manner in which it was carried out.

For the subjective tests, a comment among some jurors was that they were confused during the pass by comparisons as to whether to judge the loudness on an overall scale or by comparing the peak level (just prior to the emergency vehicle passing by). The investigator instructed the jurors to judge the peak level of the signals; the reason being that the signals did not all have the same time length. Other observations during the investigation included: jurors removing their foot off the break, causing the vehicle to accelerate forward into the traffic intersection. Other participants were observed to be re-listening to signals four or five times before arriving at a decision.

Despite the limitations and uncertainties discovered and thoroughly examined throughout the course of this research, the confidence of the stated outcomes and conclusions is still more than pleasing.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The following chapter is a reiteration of the significant conclusions resulting from this research. The purpose of the thesis was to examine present siren systems and present to the City of Windsor recommendations of the preferred audible warning system(s). In addition, factors relating to EVSN effectiveness were examined and included to better inform emergency responder personnel. The work completed was based on an extensive review of past studies, which showed missing and incomplete areas open for further investigation. The experiments conducted were designed to acquire the utmost level of information based on the set of criteria discussed. The results of the study exceeded the objectives of the research and in addition, recommendations for future work are provided.

6.1 Conclusions

As discussed in Chapter 5, the stated outcomes and conclusions focused on four principal elements, which may affect the outcomes of an emergency vehicle siren system. The first was the investigation of the shadow phenomenon. It was concluded that the presence of a blocking vehicle at traffic intersections does result in a reduction to the sound level within a receiver vehicle. It should be noted that this reduction is large enough such that it could significantly influence a driver’s ability to hear an approaching emergency vehicle.

The second element was the comparative analysis of the mechanical and the electrical siren systems. It should be noted that the latter system is replacing the mechanical siren due to lower unit cost and reduced electrical power requirement for operation. The study concluded by all the different tests conducted that the mechanical siren is a more effective siren system. This research, however, did not investigate the economic breakdown of the siren systems; the conclusions were based solely on acoustical performance.

As part of the comparison between the electrical and mechanical systems, the addition of the air horn system was included in a portion of the experiments. The inclusion of the air horn resulted in higher sound outputs of the warning system as well as perceived preference among the jurors in regards to loudness. The validation of the air horn was important to this study as no other research was found in regards to the effectiveness of using the air horn. In fact, it was found that opinions regarding the use of the air horn are generally mixed among users and researchers.

A final task of this study was the investigation of the effectiveness of the Rumbler system, which is a newly developed low frequency siren adaptation, which works in parallel with a standard electrical siren system. The investigation of the Rumbler was also included in the shadow phenomenon tests, as the addition of a low frequency system resulted in a greater ability to penetrate into a receiver vehicle. This conclusion can also be extended to other obstructions present in traffic, which can also be overcome through the implementation of the Rumbler siren. Overall, both the experimental analysis and subjective tests proved the Rumbler to be an effective emergency warning device.

Also included in the study was an investigation that compared the Wail and Yelp siren modes, both of which are typical selections on electrical siren systems. The experimental and psychoacoustic analysis did not show one siren mode to be better than the other. However, it is believed that the Yelp is the more effective option given that the cycling time of the Wail is 11 times longer than the Yelp. Analysis of the roughness metric concluded that the Yelp did have a rougher signal, which would attribute to a greater sense of urgency. This finding can be adapted to similar characteristics such as perceived annoyance and alerting nature, all of which are desirable characteristics for an emergency siren.

6.2 Recommendations

Based on the positive outcomes and stated conclusions, notable recommendations are provided. These recommendations are based on both the review of previous studies, conversation with emergency responders, combined with the observed outcomes of this research.

The most obvious recommendation taken from the results of this study is the preference of the mechanical siren system. However, it is understood that due to the increased electrical power requirements for operation of the mechanical siren (which is not available on smaller emergency vehicles), it is recommended that the mechanical system be implemented onto any vehicle that can handle the required power consumption.

It is also recommended that the air horn equipped in emergency vehicles be used with the sirens, particularly at congested traffic intersections. This recommendation is valid for both the electrical and mechanical siren systems.

Implementation of the Rumbler siren system on all emergency vehicles is also recommended, especially those that do not have, or are not capable of powering the mechanical system. For all tests, the addition of this low frequency siren system proved to be very effective and was the best siren to overcome the adverse effects of a shadow vehicle. A final recommendation is that the Yelp mode be given preference over the Wail sound for electrical siren systems.

6.3 Opportunities for Future Work

While it is evident this study attended to the goal of determining the effectiveness of several siren types, opportunities for further research and work still exist. An important aspect for future research is the investigation of methods to increase the effectiveness of siren systems without necessarily increasing the loudness of the siren. The following is detailed list for future work for the investigation of siren effectiveness:

- Further expand the research related to the shadow phenomenon, using additional vehicle types and sizes
- Examining the noise reduction characteristics of other receiving vehicles, such as luxury automobiles, which are designed to be more soundproof and having higher transmission loss characteristics
- Further investigate the effects of noise reduction of an automobile under different ambient cabin conditions, i.e. with HVAC and/or stereo system on, and windows down
- Effect on pedestrian recognition, primarily the localization of siren systems
- Expand the subjective analysis to include other psychoacoustic metrics such as perceived urgency, localisation, and alerting nature
- Incorporate driving into a jury evaluation to add better context to the subjective tests with the understanding that a more complex task will correspond to more difficulty to determine a preference

- Experimental testing of different mounting options of siren systems, i.e. outside of the front grill, or height of the siren speaker

Noting the opportunities for future work, attention to the accomplishments of this study should be addressed. The joint satisfaction of the overall contributions of this research to academia as well as to the safety and wellbeing of the general public is a feat seldom accomplished and should be used as an example for research studies of similar nature.

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Appendix A: Consent Form to Participate in Research & Letter of Information

University of Windsor

SIGNED CONSENT FORM TO PARTICIPATE IN RESEARCH

Title of Study: **Emergency Vehicle Siren Noise Effectiveness – Loudness Analysis**

You are asked to participate in a research study conducted by Peter D'Angela, from the Mechanical, Automotive, and Materials Engineering Department at the University of Windsor as part of his work for his MASc. Thesis.

If you have any questions or concerns about the research, please feel to contact Peter D'Angela at (519) 890-3652, (dangelp@uwindsor.ca); or Dr. Colin Novak at (519) 253-3000 x2634, (novak1@uwindsor.ca).

PURPOSE OF THE STUDY

The purpose of this study is to determine which siren sounds are perceived as being louder under certain conditions within a modern vehicle. This includes stationary siren sounds, including the presence of blocking/shielding vehicles, as well as drive-by analysis. A series of different siren systems and devices will be examined in the evaluation.

PROCEDURES

If you volunteer to participate in this study, you will be asked to:

Listen to a series of audio signals that have been separated into pairs. The participant is asked to select which sound (A or B) that they perceive to be of higher loudness.

The experiment will take place in a driving simulator, stationed in room 121 in the Centre for Automotive Research and Education (C.A.R.E. building) at the University of Windsor and is anticipated to take approximately 0.5 hours to complete. Extra time has been allotted should you wish to continue after stopping or take breaks.

POTENTIAL RISKS AND DISCOMFORTS

Some acoustic signals used during the assessment may cause discomfort due to their unpleasant nature. During the test if you feel uncomfortable the experiment may be stopped at any time. Should you wish to take a break, simply place the volume control on the floor of the room and the investigator will stop all signals and open the doors. (doors will remain unlocked at all times).

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

There is no direct benefit to the subjects of this study. Information gained from this research will aid in determining the effectiveness of certain sirens in relation to headphone devices. It is the intent that this study will lead to improved sirens thus improving safety of the community.

COMPENSATION FOR PARTICIPATION

Participation in this research is voluntary and you will not receive any payment for taking part in this study. Some snacks and beverages will be provided to ensure participant comfort during the test.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. No video recordings are made during this experiment and any recorded signals will remain with the primary investigator on a password protected laptop.

A1: Consent Form Page 1 of 2

PARTICIPATION AND WITHDRAWAL

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time with no consequences.

If you decide to withdraw or if you are withdrawn before the study is completed, we will ask for your permission to retain and use your data collected up to that point. If you decline permission, your data and contact information will be destroyed. However, it will only be possible to do so if they have not been included in any publication. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

If interested, a hard copy or an electronic copy of the publication would be provided to you.

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study "**Emergency Vehicle Siren Noise Effectiveness – Loudness Analysis**" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Participant

______________________________ ____________________
Signature of Participant Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

______________________________ ____________________
Signature of Investigator Date

A2: Consent Form Page 2 of 2

University of Windsor

LETTER OF INFORMATION

Title of Study: **Emergency Vehicle Siren Noise Effectiveness – Loudness Analysis**

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PROCEDURES

If you volunteer to participate in this study, you will be asked to:

Listen to a series of audio signals that have been separated into pairs. The participant is asked to select which sound (A or B) that they perceive to be of higher loudness.

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There is no direct benefit to the subjects of this study. Information gained from this research will aid in determining the effectiveness of certain sirens in relation to headphone devices. It is the intent that this study will lead to improved sirens thus improving safety of the community.

COMPENSATION FOR PARTICIPATION

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CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. No video recordings are made during this experiment and any recorded signals will remain with the primary investigator on a password protected laptop.

A3: Letter of Information Page 1 of 2

PARTICIPATION AND WITHDRAWAL

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time with no consequences.

If you decide to withdraw or if you are withdrawn before the study is completed, we will ask for your permission to retain and use your data collected up to that point. If you decline permission, your data and contact information will be destroyed. However, it will only be possible to do so if they have not been included in any publication. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

If interested, a hard copy or an electronic copy of the publication would be provided to you.

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

______________________________ ________________

Signature of Investigator Date

A4: Letter of Information Page 2 of 2

Appendix B: Jury Test Paired Comparison Matrices

Note: Yellow fill indicates a pair used for evaluation and grey fill indicates an invalid pair

B1: Electrical and mechanical siren pass-by with and without the air horn

Signal	Electrical	Electrical w/ Air Horn	Mechanical	Mechanical w/ Air Horn
Electrical				
Electrical w/ Air Horn				
Mechanical				
Mechanical w/ Air Horn				

B2: Electrical and mechanical siren with and without the presence of the shadow vehicle

Signal	Electrical No Shadow	Electrical w/ Shadow	Mechanical No Shadow	Mechanical w/ Shadow
Electrical No Shadow				
Electrical w/ Shadow				
Mechanical No Shadow				
Mechanical w/ Shadow				

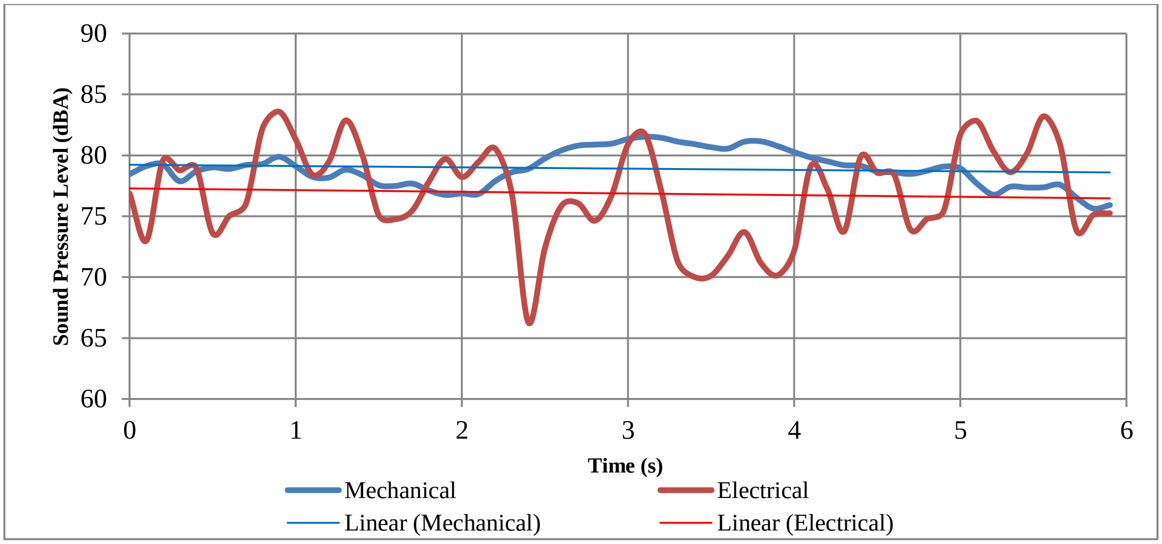
B3: Wail alone, Wail with Rumbler, and Yelp with Rumbler siren pass-by

Signal	Wail	Wail + Rumbler	Yelp + Rumbler
Wail			
Wail + Rumbler			
Yelp + Rumbler			

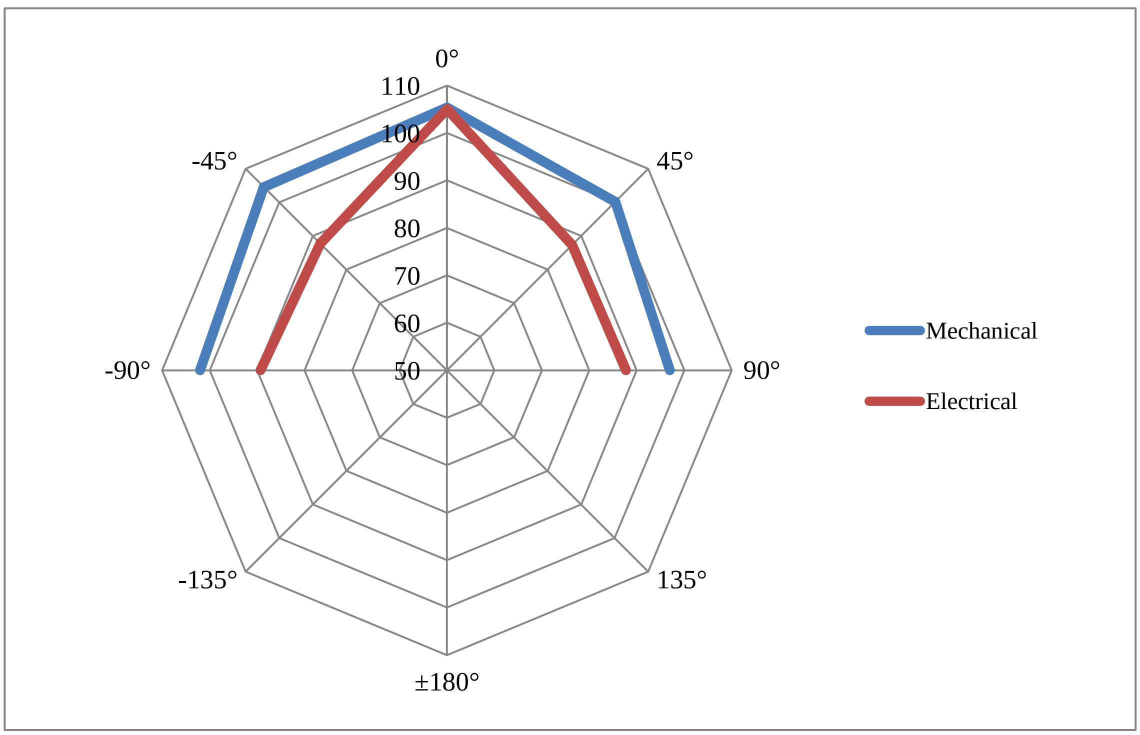
B4: Wail alone, Wail with Rumbler, and Yelp with Rumbler siren with and without the presence of the shadow vehicle

Signal	Wail + Rumbler No Shadow	Wail + Rumbler w/ Shadow	Wail No Shadow	Wail w/ Shadow	Yelp + Rumbler No Shadow	Yelp + Rumbler w/ Shadow
Wail + Rumbler No Shadow						
Wail + Rumbler w/ Shadow						
Wail No Shadow						
Wail w/ Shadow						
Yelp + Rumbler No Shadow						
Yelp + Rumbler w/ Shadow						

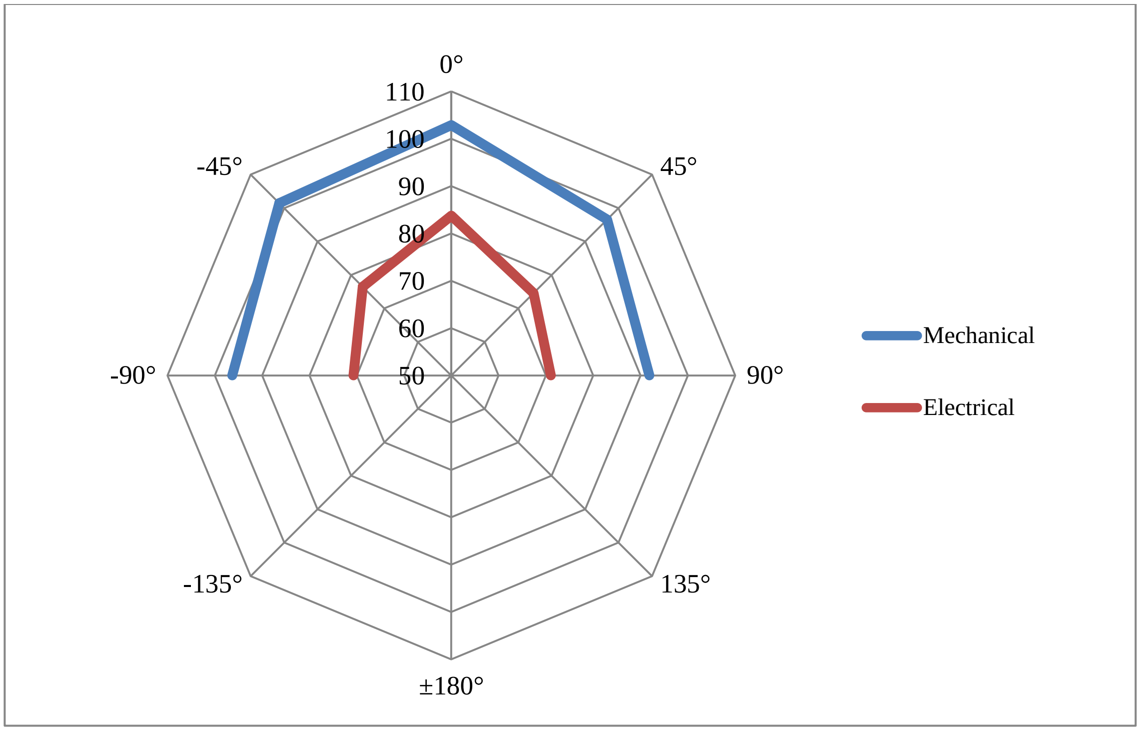
Appendix C: Mechanical v. Electrical System Comparison & Analysis with Rumbler Data Analysis Results



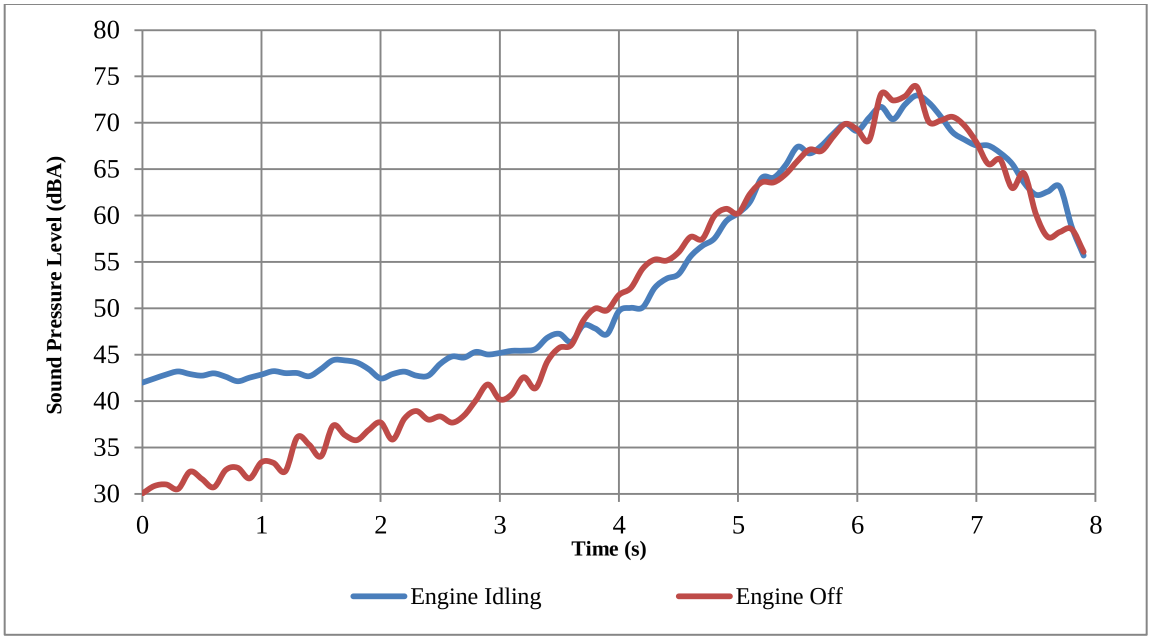
C1: A-weighting Overall Time Response of the mechanical and electrical siren since the receiver vehicle with the presence of the shadow vehicle with corresponding linear trend lines



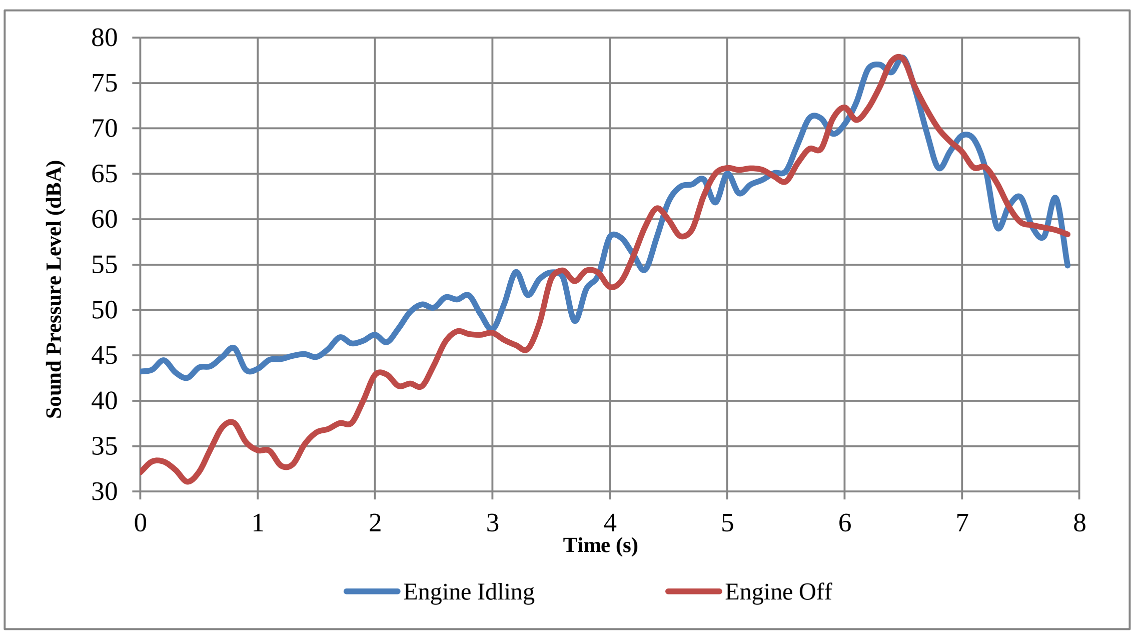
C2: Maximum A-weighted Overall Time Response of the mechanical and electrical siren frontal directivity



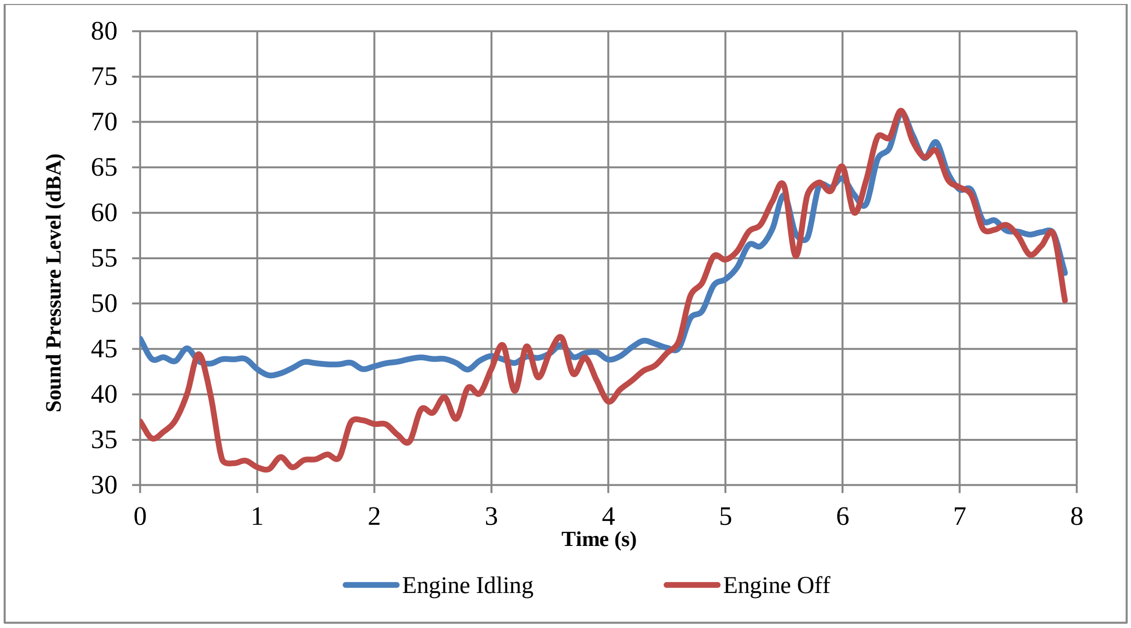
C3: Minimum A-weighted Overall Time Response of the mechanical and electrical siren frontal directivity



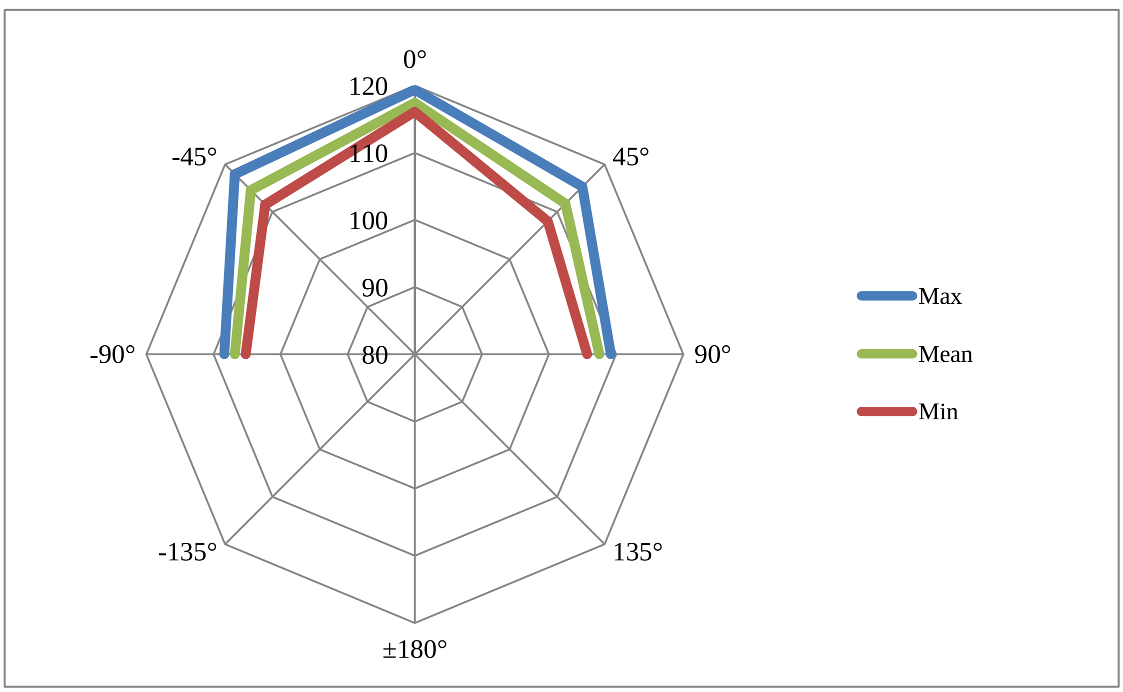
C4: A-weighted Overall Time Response of the Yelp with Rumbler siren pass-by under multiple engine conditions



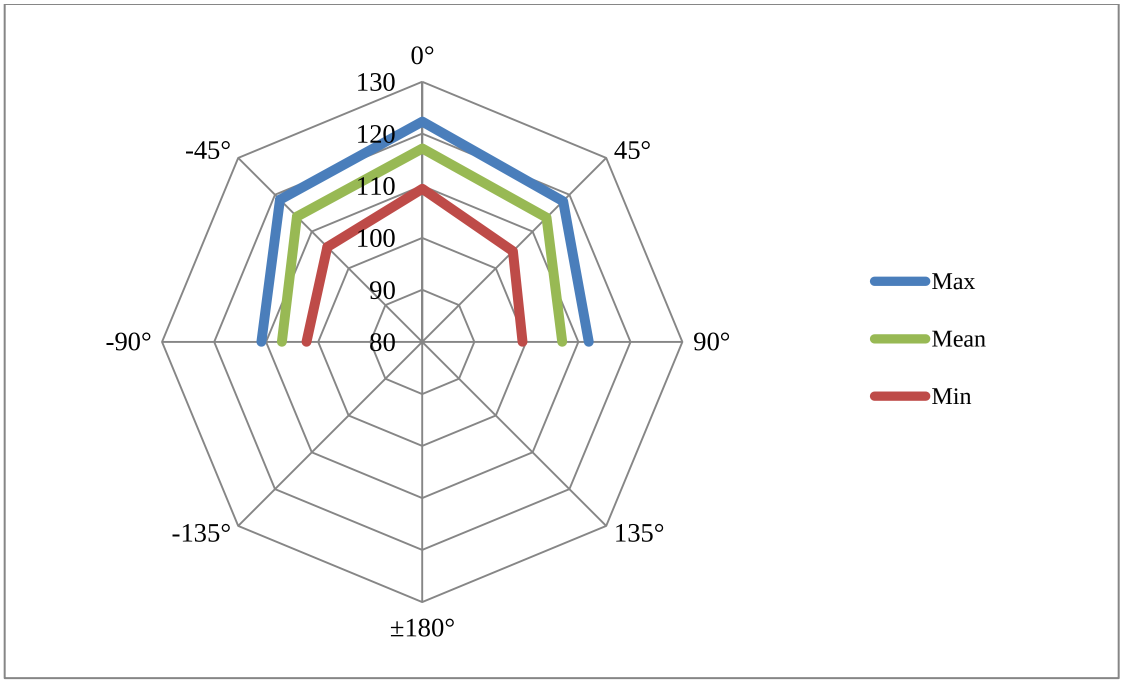
C5: A-weighted Overall Time Response of the Wail with Rumbler siren pass-by under multiple engine conditions



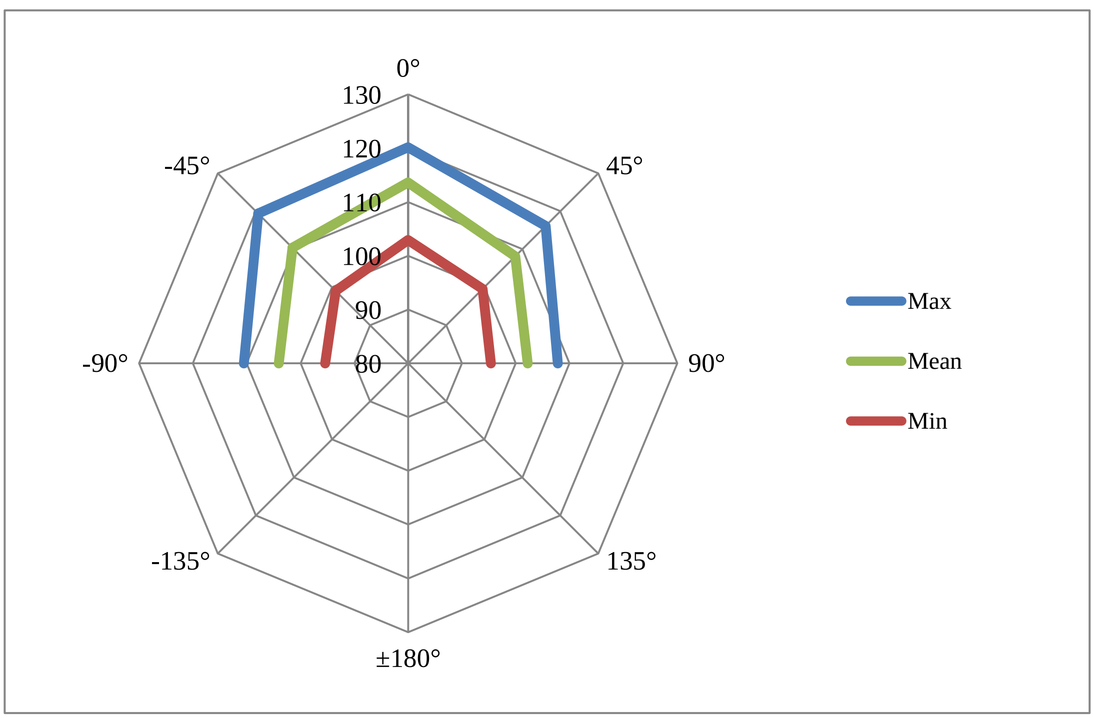
C6: A-weighted Overall Time Response of the Wail alone siren pass-by under multiple engine conditions



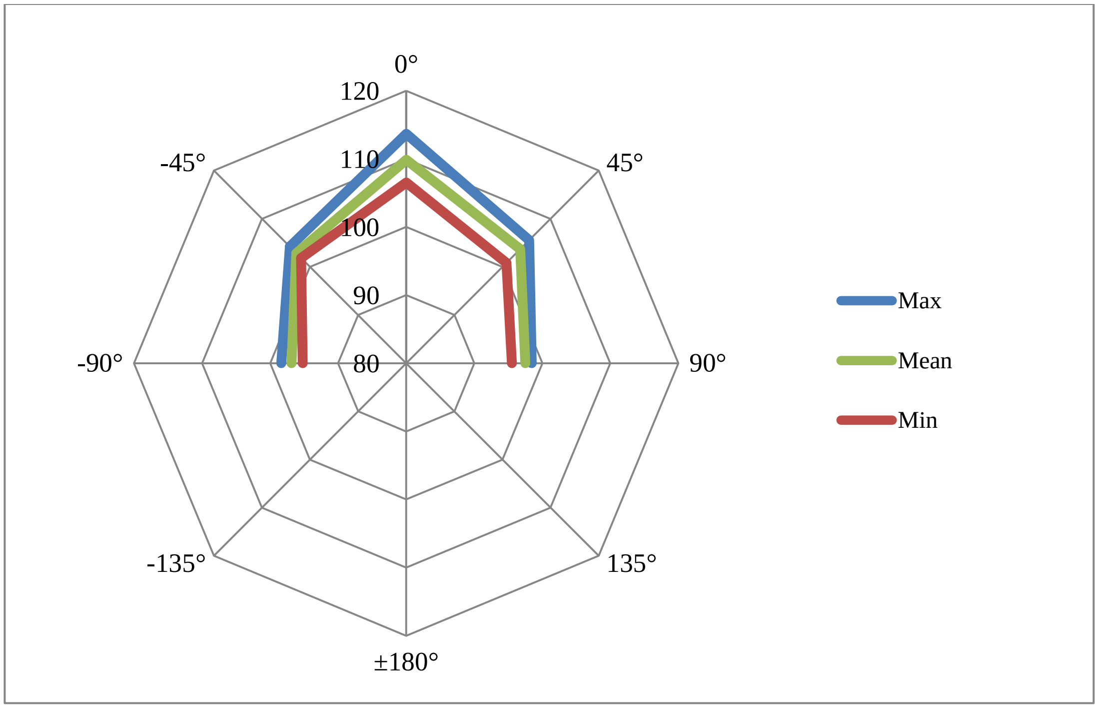
C7: A-weighted Overall Time Response of the Yelp with the Rumbler siren frontal directivity at a measurement distance of 5 m



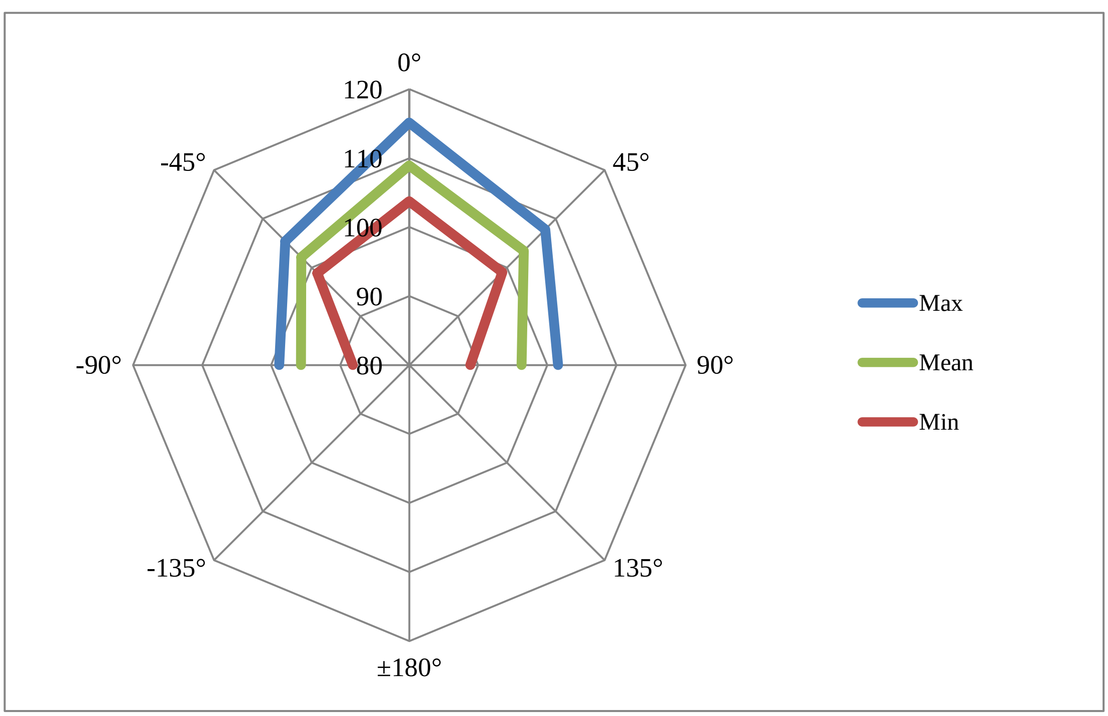
C8: A-weighted Overall Time Response of the Wail with the Rumbler siren frontal directivity at a measurement distance of 5 m



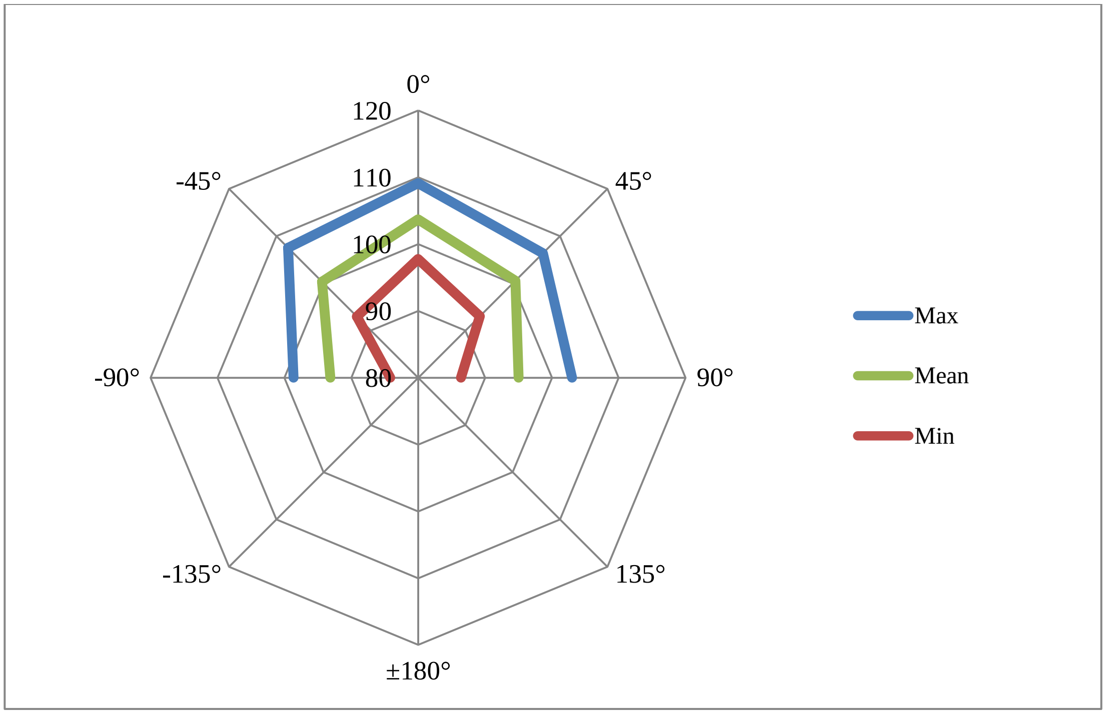
C9: A-weighted Overall Time Response of the Wail alone siren frontal directivity at a measurement distance of 5 m



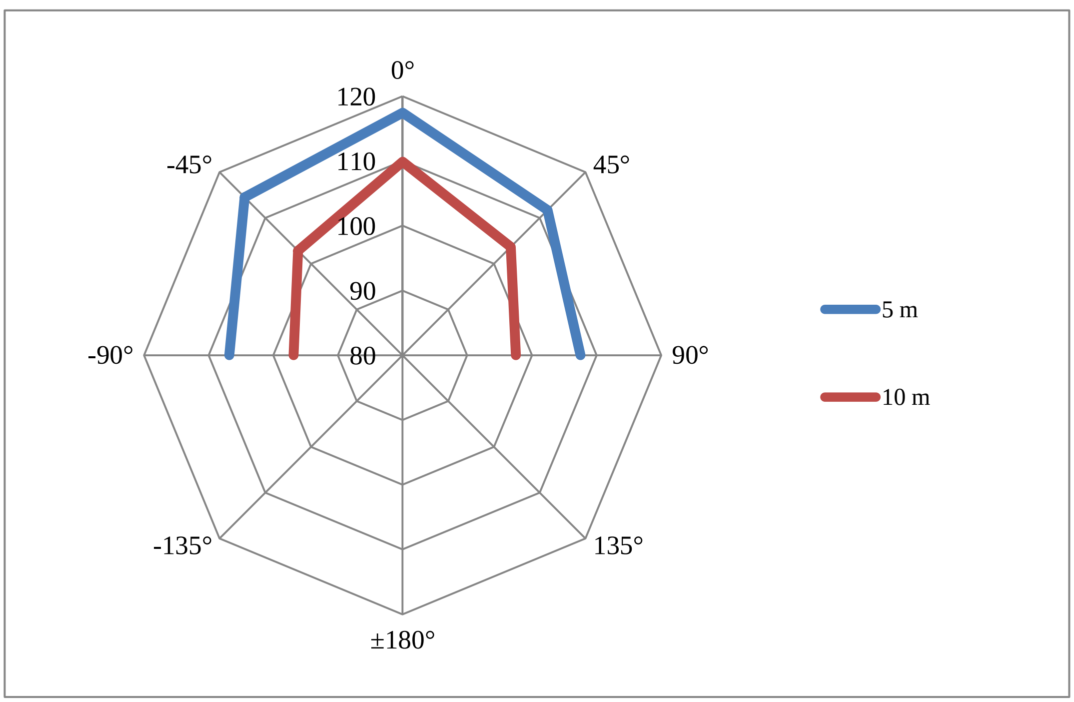
C10: A-weighted Overall Time Response of the Yelp with the Rumbler siren frontal directivity at a measurement distance of 10 m



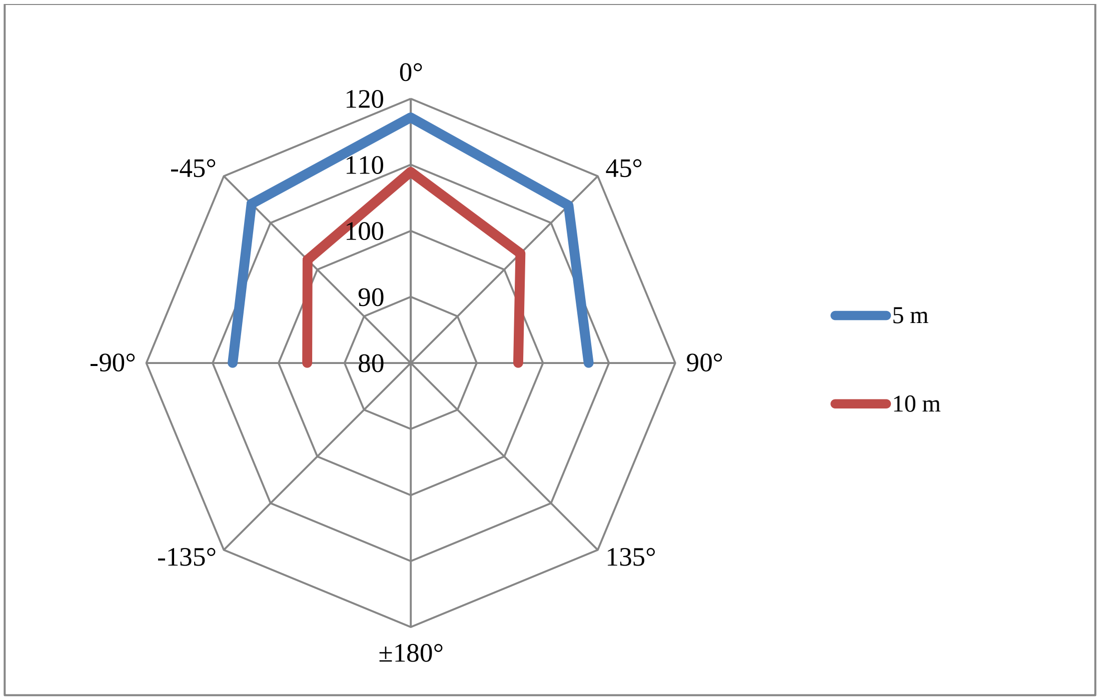
C11: A-weighted Overall Time Response of the Wail with the Rumbler siren frontal directivity at a measurement distance of 10 m



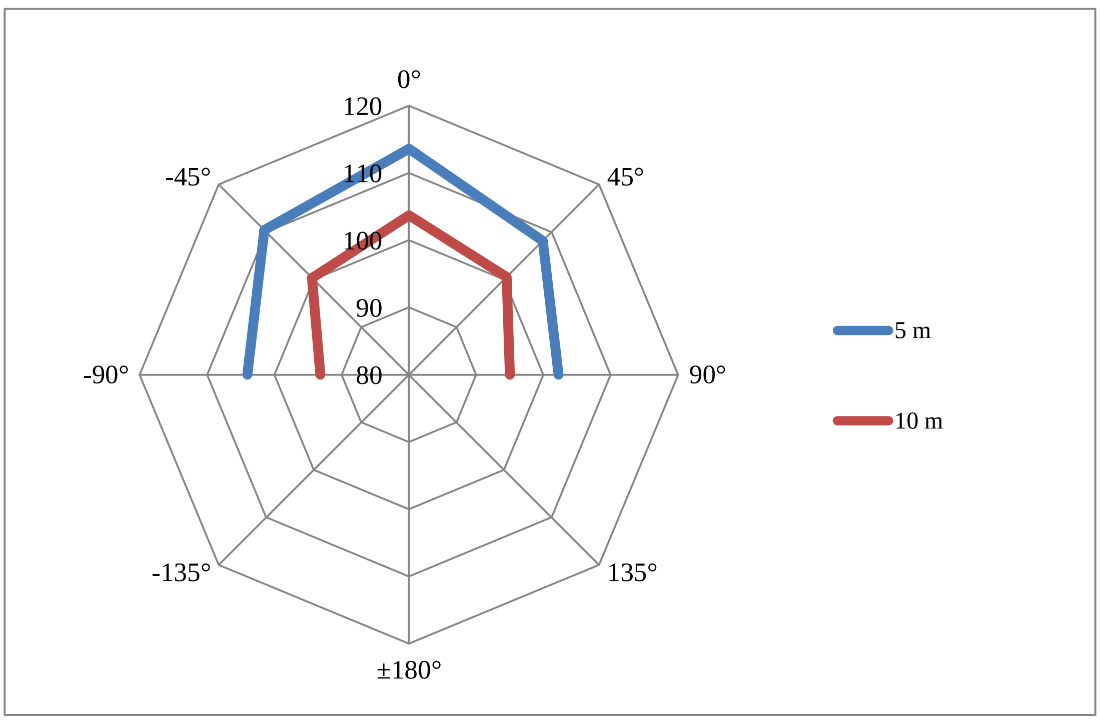
C12: A-weighted Overall Time Response of the Wail alone siren frontal directivity at a measurement distance of 10 m



C13: Mean A-weighted Overall Time Response of the Yelp with the Rumbler siren frontal directivity at measurement distances of 5m and 10 m



C14: Mean A-weighted Overall Time Response of the Wail with the Rumbler siren frontal directivity at measurement distances of 5m and 10 m



C15: Mean A-weighted Overall Time Response of the Wail alone siren frontal directivity at measurement distances of 5m and 10 m

Appendix D: Psychoacoustic Analysis using Objective Sound Quality Metrics and Subjective Testing Results

D1: Jury evaluation scores, participants 1 to 9

Pair #	Type	Signal	Option	Juror # / Gender								
				1 F	2 M	3 M	4 M	5 M	6 F	7 M	8 F	9 F
1	Pass-by	YR	A									
		WR	B	X	X	X	X	X	X	X	X	X
2	Shadow	WR	A	X	X	X	X	X	X	X	X	X
		WR w/S	B									
3	Pass-by	E	A									
		M	B	X	X	X	X	X	X	X	X	X
4	Shadow	YR w/S	A									
		YR	B	X	X	X	X	X	X	X	X	X
5	Pass-by	M	A									
		M w/A	B	X	X	X	X	X	X	X	X	X
6	Shadow	M w/S	A									
		M	B	X	X	X	X	X	X	X	X	X
7	Shadow	YR w/S	A	X	X	X		X	X	X	X	X
		WR w/S	B				X					
8	Pass-by	W	A							X		
		YR	B	X	X	X	X	X	X		X	X
9	Shadow	E	A	X	X	X	X	X	X	X	X	X
		E w/S	B									
10	Shadow	W w/S	A									
		WR w/S	B	X	X	X	X	X	X	X	X	X
11	Pass-by	E w/A	A	X	X	X		X	X	X	X	X
		E	B				X					
12	Shadow	WR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
13	Shadow	M w/S	A	X	X	X	X	X	X	X		X
		E w/S	B								X	
14	Shadow	W w/S	A						X	X		
		YR w/S	B	X	X	X	X	X			X	X
15	Pass-by	E w/A	A									
		M w/A	B	X	X	X	X	X	X	X	X	X
16	Pass-by	M	A	X	X	X		X		X	X	X
		E	B				X		X			
17	Shadow	W w/S	A								X	
		W	B	X	X	X	X	X	X	X		X
18	Pass-by	W	A									

		WR	B	X	X	X	X	X	X	X	X	X
19	Pass-by	E	A									
		E w/A	B	X	X	X	X	X	X	X	X	X
20	Shadow	E w/S	A							X		
		M w/S	B	X	X	X	X	X	X		X	X
21	Shadow	WR w/S	A			X		X	X	X		
		YR w/S	B	X	X		X				X	X
22	Shadow	WR w/S	A									
		WR	B	X	X	X	X	X	X	X	X	X
23	Shadow	YR	A	X	X	X	X	X	X	X	X	X
		YR w/S	B									
24	Shadow	E w/S	A									
		E	B	X	X	X	X	X	X	X	X	X
25	Pass-by	M w/A	A	X	X	X	X	X	X	X		X
		M	B								X	
26	Pass-by	YR	A	X	X		X	X	X	X	X	X
		W	B			X						
27	Shadow	W	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
28	Pass-by	WR	A	X		X	X	X			X	X
		YR	B		X				X	X		
29	Shadow	YR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
30	Shadow	M	A	X	X	X	X	X	X	X	X	X
		M w/S	B									
31	Pass-by	WR	A	X	X	X	X	X	X	X	X	X
		W	B									
32	Pass-by	M w/A	A	X	X	X	X	X	X	X	X	X
		E w/A	B									

D2: Jury evaluation scores, participants 10 to 18

Pair #	Type	Signal	Option	Juror # / Gender								
				10 M	11 F	12 F	13 M	14 F	15 M	16 M	17 M	18 M
1	Pass-by	YR	A				X		X			X
		WR	B	X	X	X		X		X	X	
2	Shadow	WR	A	X	X	X	X	X	X	X	X	X
		WR w/S	B									
3	Pass-by	E	A		X							
		M	B	X		X	X	X	X	X	X	X
4	Shadow	YR w/S	A									
		YR	B	X	X	X	X	X	X	X	X	X
5	Pass-by	M	A									
		M w/A	B	X	X	X	X	X	X	X	X	X
6	Shadow	M w/S	A									
		M	B	X	X	X	X	X	X	X	X	X
7	Shadow	YR w/S	A	X	X	X	X	X	X	X	X	X
		WR w/S	B									
8	Pass-by	W	A								X	
		YR	B	X	X	X	X	X	X	X		X
9	Shadow	E	A	X	X	X	X	X	X	X	X	X
		E w/S	B									
10	Shadow	W w/S	A									
		WR w/S	B	X	X	X	X	X	X	X	X	X
11	Pass-by	E w/A	A	X		X	X	X	X	X	X	X
		E	B		X							
12	Shadow	WR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
13	Shadow	M w/S	A	X	X	X	X	X	X	X	X	X
		E w/S	B									
14	Shadow	W w/S	A									
		YR w/S	B	X	X	X	X	X	X	X	X	X
15	Pass-by	E w/A	A									
		M w/A	B	X	X	X	X	X	X	X	X	X
16	Pass-by	M	A	X	X	X	X		X		X	
		E	B					X		X		X
17	Shadow	W w/S	A									
		W	B	X	X	X	X	X	X	X	X	X
18	Pass-by	W	A				X					X
		WR	B	X	X	X		X	X	X	X	
19	Pass-by	E	A		X							
		E w/A	B	X		X	X	X	X	X	X	X

20	Shadow	E w/S	A									
		M w/S	B	X	X	X	X	X	X	X	X	X
21	Shadow	WR w/S	A				X	X		X		X
		YR w/S	B	X	X	X			X		X	
22	Shadow	WR w/S	A									
		WR	B	X	X	X	X	X	X	X	X	X
23	Shadow	YR	A	X	X	X	X	X	X	X	X	X
		YR w/S	B									
24	Shadow	E w/S	A									
		E	B	X	X	X	X	X	X	X	X	X
25	Pass-by	M w/A	A	X	X	X	X	X	X	X	X	X
		M	B									
26	Pass-by	YR	A	X	X		X	X	X	X	X	X
		W	B			X						
27	Shadow	W	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
28	Pass-by	WR	A		X	X				X	X	X
		YR	B	X			X	X	X			
29	Shadow	YR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
30	Shadow	M	A	X	X	X	X	X	X	X	X	X
		M w/S	B									
31	Pass-by	WR	A	X	X	X	X	X	X	X	X	
		W	B									X
32	Pass-by	M w/A	A	X	X		X	X	X	X	X	X
		E w/A	B			X						

D3: Jury evaluation scores, participants 19 to 27

Pair #	Type	Signal	Option	Juror # / Gender								
				19 M	20 F	21 M	22 M	23 M	24 F	25 M	26 M	27 F
1	Pass-by	YR	A									
		WR	B	X	X	X	X	X	X	X	X	X
2	Shadow	WR	A	X	X	X	X	X	X	X	X	X
		WR w/S	B									
3	Pass-by	E	A									
		M	B	X	X	X	X	X	X	X	X	X
4	Shadow	YR w/S	A									
		YR	B	X	X	X	X	X	X	X	X	X
5	Pass-by	M	A									
		M w/A	B	X	X	X	X	X	X	X	X	X
6	Shadow	M w/S	A									
		M	B	X	X	X	X	X	X	X	X	X
7	Shadow	YR w/S	A	X		X		X	X	X	X	X
		WR w/S	B		X		X					
8	Pass-by	W	A									
		YR	B	X	X	X	X	X	X	X	X	X
9	Shadow	E	A	X	X	X	X	X	X	X	X	X
		E w/S	B									
10	Shadow	W w/S	A									
		WR w/S	B	X	X	X	X	X	X	X	X	X
11	Pass-by	E w/A	A	X	X	X	X	X	X		X	X
		E	B							X		
12	Shadow	WR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
13	Shadow	M w/S	A	X	X	X	X	X	X	X	X	X
		E w/S	B									
14	Shadow	W w/S	A							X		
		YR w/S	B	X	X	X	X	X	X		X	X
15	Pass-by	E w/A	A							X		
		M w/A	B	X	X	X	X	X	X		X	X
16	Pass-by	M	A	X	X	X	X	X	X		X	X
		E	B							X		
17	Shadow	W w/S	A									
		W	B	X	X	X	X	X	X	X	X	X
18	Pass-by	W	A									
		WR	B	X	X	X	X	X	X	X	X	X
19	Pass-by	E	A									
		E w/A	B	X	X	X	X	X	X	X	X	X

20	Shadow	E w/S	A							X		
		M w/S	B	X	X	X	X	X	X		X	X
21	Shadow	WR w/S	A	X			X					
		YR w/S	B		X	X		X	X	X	X	X
22	Shadow	WR w/S	A									
		WR	B	X	X	X	X	X	X	X	X	X
23	Shadow	YR	A	X	X	X	X	X	X	X	X	X
		YR w/S	B									
24	Shadow	E w/S	A									
		E	B	X	X	X	X	X	X	X	X	X
25	Pass-by	M w/A	A	X	X	X	X	X	X	X	X	X
		M	B									
26	Pass-by	YR	A	X	X	X	X	X	X	X	X	X
		W	B									
27	Shadow	W	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
28	Pass-by	WR	A	X	X	X	X			X	X	
		YR	B					X	X			X
29	Shadow	YR w/S	A	X	X	X	X	X	X	X	X	X
		W w/S	B									
30	Shadow	M	A	X	X	X	X	X	X	X	X	X
		M w/S	B									
31	Pass-by	WR	A	X	X	X	X	X	X	X	X	X
		W	B									
32	Pass-by	M w/A	A	X	X	X	X	X	X		X	X
		E w/A	B							X		

D4: Jury evaluation scores, participants 28 to 32

Pair #	Type	Signal	Option	Juror # / Gender				
				28 M	29 F	30 M	31 M	32 F
1	Pass-by	YR	A					X
		WR	B	X	X	X	X	
2	Shadow	WR	A	X	X	X	X	X
		WR w/S	B					
3	Pass-by	E	A					
		M	B	X	X	X	X	X
4	Shadow	YR w/S	A					
		YR	B	X	X	X	X	X
5	Pass-by	M	A					
		M w/A	B	X	X	X	X	X
6	Shadow	M w/S	A	X				
		M	B		X	X	X	X
7	Shadow	YR w/S	A	X		X		X
		WR w/S	B		X		X	
8	Pass-by	W	A		X			
		YR	B	X		X	X	X
9	Shadow	E	A	X	X	X	X	X
		E w/S	B					
10	Shadow	W w/S	A					
		WR w/S	B	X	X	X	X	X
11	Pass-by	E w/A	A	X	X	X	X	X
		E	B					
12	Shadow	WR w/S	A	X	X	X	X	X
		W w/S	B					
13	Shadow	M w/S	A	X	X	X	X	X
		E w/S	B					
14	Shadow	W w/S	A					
		YR w/S	B	X	X	X	X	X
15	Pass-by	E w/A	A					
		M w/A	B	X	X	X	X	X
16	Pass-by	M	A	X	X	X	X	X
		E	B					
17	Shadow	W w/S	A					
		W	B	X	X	X	X	X
18	Pass-by	W	A					
		WR	B	X	X	X	X	X
19	Pass-by	E	A					
		E w/A	B	X	X	X	X	X

20	Shadow	E w/S	A					
		M w/S	B	X	X	X	X	X
21	Shadow	WR w/S	A	X			X	
		YR w/S	B		X	X		X
22	Shadow	WR w/S	A					
		WR	B	X	X	X	X	X
23	Shadow	YR	A	X	X	X	X	X
		YR w/S	B					
24	Shadow	E w/S	A					
		E	B	X	X	X	X	X
25	Pass-by	M w/A	A	X	X	X	X	X
		M	B					
26	Pass-by	YR	A		X	X	X	
		W	B	X				X
27	Shadow	W	A	X	X	X	X	X
		W w/S	B					
28	Pass-by	WR	A	X		X	X	X
		YR	B		X			
29	Shadow	YR w/S	A	X	X	X	X	X
		W w/S	B					
30	Shadow	M	A	X	X	X	X	X
		M w/S	B					
31	Pass-by	WR	A	X	X	X	X	
		W	B					X
32	Pass-by	M w/A	A	X	X	X	X	X
		E w/A	B					

D5: Siren signal total and merit scores from jury evaluation

Car Name	Total Score	Merit Score
Cop Cruiser - Pass-by - Wail	1	-3.5
Cop Cruiser - Pass-by - Wail + Rumbler	47	5.0
Cop Cruiser - Pass-by - Yelp + Rumbler	27	-1.4
Cop Cruiser - Shadow - Wail + Rumbler No Shadow	32	2.9
Cop Cruiser - Shadow - Wail + Rumbler w Shadow	34	-0.1
Cop Cruiser - Shadow - Wail No Shadow	31	2.9
Cop Cruiser - Shadow - Wail w Shadow	0	-8.2
Cop Cruiser - Shadow - Yelp + Rumbler No Shadow	32	2.9
Cop Cruiser - Shadow - Yelp + Rumbler w Shadow	46	-0.6
Fire Truck - Pass-by - Electrical	1	-3.5
Fire Truck - Pass-by - Electrical w/ Air Horn	30	0.0
Fire Truck - Pass-by - Mechanical	25	-2.2
Fire Truck - Pass-by - Mechanical w/ Air Horn	60	5.7
Fire Truck - Shadow - Electrical No Shadow	32	2.9
Fire Truck - Shadow - Electrical w Shadow	0	-4.9
Fire Truck - Shadow - Mechanical No Shadow	31	2.9
Fire Truck - Shadow - Mechanical w Shadow	28	-1.0

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