DESIGN AND CONFIGURATION OF AUDIBLE PEDESTRIAN SIGNALS IN THE CITY OF WINNIPEG

by

Mohammed Elias Ahmed

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

In partial fulfillment of the requirements of the degree of

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DESIGN AND CONFIGURATION OF AUDIBLE PEDESTRIAN SIGNALS IN THE CITY OF WINNIPEG

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ABSTRACT

The city of Winnipeg is making a continuous effort to improve city accessibility. One of the projects the city has implemented to achieve this goal was installing audible traffic signals (ATS) at some intersections to help visually impaired people (VIP) to cross the streets safely. These ATSs were installed at about 200 intersections so far. However the performance of these systems was not satisfactory due to inconsistent audibility resulting from various aspects such as; traffic noise, wind interference, existence of high rise buildings around intersections, etc. This research outlines the specific issues surrounding the current system and suggests the potential solutions to counteract them.

Design of experiments was used to analyze the effectiveness of the ATS system in different levels of speaker height, seasons, number of lanes, and existence of high-rise buildings nearby. Data was collected from a questionnaire through a set of tests conducted at intersections with the help of 16 VIPs. Conclusions were drawn based on the Analysis of Variance (ANOVA) using the MINITAB® software. Finally, the results were reported along with the recommendations related to the system design and maintenance. One of the main recommendations was to lower the speaker height to 4 feet (1.22 meters) instead of the current 10 feet (3.05 meters) height.

In view of the results that manifested from the experiments and to counter all other known issues such as echoing effects, annoyance in the neighbourhood, vandalism, etc., a new design of the ATS speaker also has been developed in this thesis and its prototypes submitted to the Public Works Department City for their consideration to implement in the city of Winnipeg.

ACKNOWLEDGEMENT

Many people have been involved in this research project and without their support it would have been difficult to accomplish this work. I would like to express my deepest gratitude to my advisor, Dr. Tarek ElMekkawy for his invaluable support and advice that helped me complete this dissertation.

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I also thank Dr. Doug Strong for his input to the development of the conceptual design and while making the prototype of the new speaker. I truly appreciate the effort of the undergraduate student Jordan Lanoway for his assistance in data collection during winter; and the graduate student Sherif Fahmy for his help in designing the experiments and making the prototype drawings. Last, but not the least; I would like to thank my family for their patience and support during my graduate study.

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CHAPTER 1

INTRODUCTION

1.1 Background

In the past years, various techniques have been tried by the visually impaired community to cross the streets at the intersections even before the introduction of the audible pedestrian signals. These techniques and cues used in crossing streets are diverse and vary by location and individual. In the absence of ATSs the most commonly used techniques for crossing the intersection is by judging the traffic by the vehicular sounds and crossing the street that is perpendicular to the street with moving traffic. However, there are always some new barriers at some intersections due to the intersection geometries, acoustic conditions, and traffic control systems. These barriers make it difficult for persons who are visually impaired to get the indication necessary to cross streets independently and safely. In these circumstances, audible traffic signal technologies can be helpful to pedestrians.

Many countries such as US, Australia, Hong Kong, Sweden, Germany, Denmark, Belgium and Austria use these pedestrian signals much more widely than that has been done in Canada. The Canadian National Institute for the Blind (CNIB) reports that as of 2002 there are over 100,000 registered visually impaired citizens across Canada. Of these, atleast 5,000 are Manitobans from a total Manitoba population of 1.16 million i.e. 0.43 % approx [CNIB statistics 2002, Manitoba Health Population Report 2002]. Moreover, the Canadian human rights commission also insists on promoting human rights for persons with disabilities. The above reasons signify our effort and investment for improving the performance of ATS systems. In Winnipeg these pedestrian signals were introduced as early as 1970's deploying bells and buzzers. But as it is well known that changes to traffic signal systems cannot be made overnight and those municipalities or transportation departments have many projects competing for their budgets. Hence the city of Winnipeg has been striving to gradually make these systems more viable and accessible.

1.2 Introduction

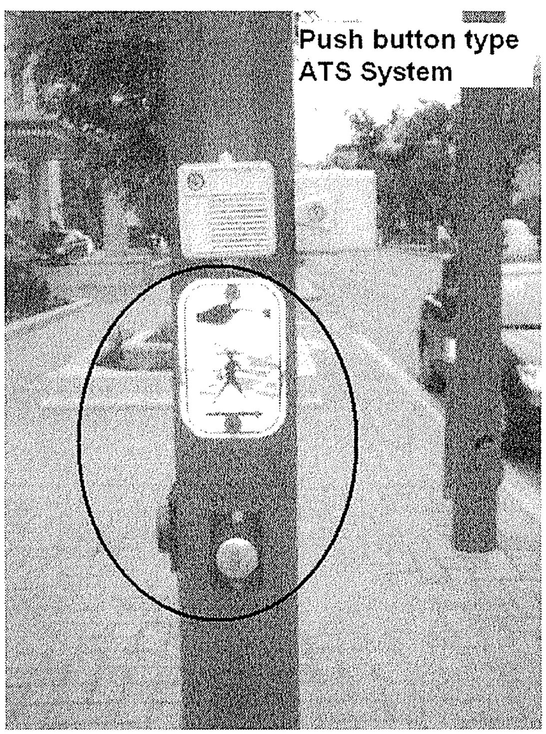
The term "Audible Traffic Signal" means a traffic signal which can be heard by the pedestrians while crossing the street. It was used when the first Audible Pedestrian Signal Standard was introduced in Canada. This Audible Pedestrian Signal standard, served as a basic and necessary accessibility feature at street crossings, particularly for persons who were visually impaired or blind.

The audible pedestrian traffic signals are used because a number of visually impaired pedestrians want to be mobile and walk in different directions to reach their destinations in different places. Therefore, they may quite often need to cross streets which have a flowing vehicular traffic. The audible signals help them to communicate with the flowing traffic to know when it is safe to cross the street and facilitate crossing the street. The audible traffic signals normally require the use of a locator tone to identify the crossing point at any traffic intersection and the use of a crossing tone to identify the other end of the crosswalk.

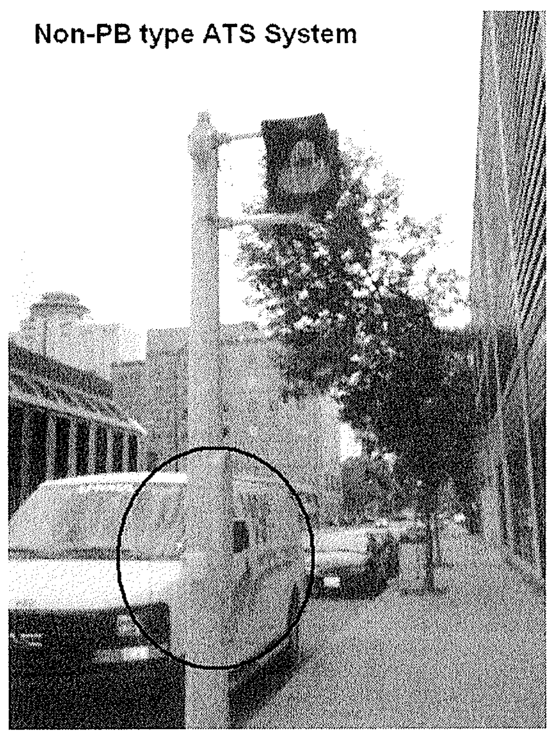
The locating tone is an intermittent ticking sound that assists pedestrians to locate the crossing point by providing them with a sense of the poles location. It is emitted from the speakers placed on the poles and is active at all times except for when a crossing tone is in operation.

The crossing tones are those which begin to sound once the traffic light changes to convey to the pedestrians that it is safe to cross the street and are emitted from the same speakers as the locating tones. To ensure the pedestrians will not be confused as to which direction is safe to cross, the crossing tones for the North-South and East-West directions emit different sounds. For example, "Cuckoo" sound for north-south direction such as walking along Fort Street crossing Broadway and "Chirp" sound for east-west direction such as walking along Broadway crossing Fort Street. Both speakers at each ends of the crosswalk emit same tone at the same frequency and intensity. The crossing tone stops when the flashing hand begins, which means do not begin crossing the street because there is not enough time to cross the street and to alert those who are already in the crosswalk so that they have enough time to cross. The flashing hand begins just a few seconds before the end of the total pre-programmed crossing time. The crossing tone not only conveys the message to the blind pedestrians to cross the street but also guides them about the direction of their travel.

A pedestrian who wants to cross the street first locates the intersection's crossing point with the help of the locating tone. If the kind of system used there is a push button type, then the pedestrian activates the push button by keeping the button pushed for about 5 seconds until the crossing tone is heard (figure 1.1. a). While on the other hand a non-push button type system doesn't need to be activated; they run at all times acting as both crossing and locating tones (figure 1.1. b). The non-push button type system is very helpful to the pedestrians who carry guide dogs or those who are physically handicapped or for the pedestrians whose both hands occupied and it is difficult to use the typical activation button on a push button type system. This kind of the system is installed at the intersection of Donald Street & York Avenue and the intersection of Smith Street & York Avenue on an experimental basis. This kind of the system is installed at the intersection of Donald Street & York Avenue and the intersection of Smith Street & York Avenue in Winnipeg for investigational purposes.



(a)



(b)

Figure 1.1: City of Winnipeg's existing ATS systems.

The current ATS systems in the city of Winnipeg in either of these two types of systems, the tone emitting speakers are normally placed at a height of 10 feet (12 feet at some places) above the ground level. Moreover they are set to the same standard volume setting of 5 dB to 9 dB above the ambient noise level to last for about 7 seconds. The volume is automatically controlled by an auto-volume sensors ensuring that the tone is audible at all times over the ambient traffic noise. Thus, it also reduces the annoyance to the neighborhood by reducing the tone volume in the absence of the traffic.

1.3 Other Systems

Other than the above mentioned types of systems, there is a variety of various other kinds of systems used in different cities in the world. A few of these systems are discussed below.

Push button – integrated: This type of system has been commonly used in Europe and Australia for years. It has a speaker and a vibrating surface or arrow at the pedestrian button. The sound comes from the push button pedestrian housing, rather than the Pedhead and it can be used at both actuated and fixed-time signal timing locations. A locator tone that repeats every second constantly provides information to the blind person about the presence of a pedestrian push button and its location and it is intended to be audible only 2-4 meters from the pole.

Vibrotactile: This type of ATS has an arrow or button that vibrates rapidly during the walk interval but there is no audible indication. Devices of this type are useful to blind pedestrians only when they know the pushbuttons exist and know where to find them.

Receiver-based: With this kind of system, users scan with receivers for pedestrian signal information as they approach the street. When receivers are oriented in the direction of pedestrian signals, a prerecorded message corresponding to the status of the signal is received. Receiver-based systems can provide clear, unambiguous information and directional guidance at typical intersections where there are more than four crosswalks and when tones may overlap and therefore be misleading. Information is available only to individuals who have the receivers and not audible to others.

All these systems discussed above have their own advantages and they have proved to be quite efficient and versatile. But these systems are not adaptable for the kind of the weather existing in Winnipeg. This sounds quite obvious as it has been noted that these systems utilize either a vibrating surface or the use of a pedestrian signal receiver which may not be possible or convenient while wearing the winter wear in extreme cold conditions in the city.

1.4 Problem Statement

Inspite of the City of Winnipeg - Public Works Department's concerted effort for the past few years to improve the effectiveness of the audible pedestrian signal systems, the current system in Winnipeg is causing a variety of barriers for the persons with visual impairments. To list a few, these issues include –

- Some speaker sound boxes are too high off the ground to provide adequate sound for persons using the audible signals. This makes it difficult for the pedestrians to locate a push button and determine the crossing point. Moreover the pedestrians may lose their sense of direction and may not cross the street on time.
- At a few intersections, it has been noticed that the ATS speaker sound boxes generated sound that is annoying to people living in immediate proximity. This was reflected by many complaints received by the City of Winnipeg.
- The ATS Speaker sound boxes mounted at lower heights have been vandalized in the past.
- In addition to the above, there were also complaints that it was sometimes confusing to determine if there is a push button or not.

1.5 Research Objective

To assist the City of Winnipeg's Public Works Department in identifying the root causes of all the issues addressed in the previous section. Eliminate the barriers that are preventing the existing system from realizing its potential benefits through an intensive research and a thorough analysis. To achieve this objective and identify the best viable solution two goals have been set.

1. Investigate and evaluate the performance of the ATS system at varying levels of speaker height, activation system, seasons, street width and complexity and make specific recommendations regarding its future configuration.

2. Custom design a speaker that can be mounted more streamlined on the pole or inside the pole whose sound level is pre-set to a level which can be clearly heard by a person with visual impairment, meet community usability needs without disturbing the people living close by in the community, reliable enough to withstand the extreme weather conditions and durable enough to endure the vandalism.

1.6 Research Approach

To achieve the given objectives, the research has been designed as follows.

1. Selected about 16 subjects (volunteers) from the visually handicapped community whose vision is between 0% to 10 %, to assess the performance of the system and identify the potential barriers in using these systems. In order to have the volunteers participate in the testing, all volunteers had to sign a consent form (refer to Appendix 1) assuring their anonymity throughout the project and informing them about the purpose of the experiments.
2. Selected four different intersections in the city and designed a set of experiments to do an actual real-time testing on the current signal systems with the help of the appointed volunteers. Each selected intersection possessed a unique property set allowing for direct comparison of each variable as detailed in Chapter 3 (Table 3.1) of this thesis.
3. Collected data by repeating the experiment with each subject individually at all intersections in both directions North/South and East/West considering various factors and at peak traffic conditions.

4. Evaluated the data by doing an analysis of variance (ANOVA) to compare performance at each intersection, at different speaker heights, at streets with different widths – with or without median and in both seasons.
5. Custom designed a special speaker using the concept of an exponential horn to generate more dynamic and efficient tones which are easily audible to the pedestrians using the ATS system without disturbing the people living close by in the community.
6. Concluded with specific recommendations for the overall enhancement of the systems and discussions relating to the directions for future work.

1.7 Thesis Organization

The complete thesis has been divided into 7 chapters. The next chapter gives an overview of all the research work done in the past on pedestrian crossing and the ATS system technology. The detailed description of the approach; an overview & basics of experimental design and the method the experiments are covered in the third chapter. The forth chapter is devoted to the analysis of the experiments. Apart from the analysis and its conclusions, there are a few other issues that are identified during the experiments which are discussed in the fifth chapter. A new design of the ATS speaker is proposed in chapter six. The thesis concludes with chapter seven summarizing the final results of the analysis and recommendation of directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

ATSs are used in many countries including Canada, the United States, Japan, Australia, New Zealand, Sweden & Scotland. Gradually many other countries also are initiating their plans to implement these systems in their major cities. In Canada, Hamilton Associates concluded their foremost research and recommended methods to address noise that are more acceptable to advocacy groups in the City of Surrey, British Columbia. Canadian National Institute for the Blind (CNIB) is addressing several issues in general and updating the set of guidelines and the criteria of ATS in Canada from time to time.

The design and operational issues surrounding the ATS systems have drawn much attention during the past decade. Such issues usually fall into one of two categories: finding a suitable signal type or tone to emit and defining the mode of operation of the signals. The objective in finding a suitable signal is to ensure that it can be effectively heard and distinguished by the impaired pedestrians. However, not only is it required that the signal can be distinguished from other street noises, but it must also be able to give a good sense of direction to the pedestrian. If orientation is lost while crossing the streets, disastrous consequences can occur. To give a broad and unambiguous overview of the pedestrian orientation and all other components involved in an ATS system the following survey has been carried out.

To better understand the perception of each element of the ATS system this survey is sub-divided into four sections as mentioned below and arranged in a chronological order within each section.

- Types of audible signals
- Operation modes
- Pedestrian orientation and behaviour.
- Modern devices and the recent developments.

2.2 Types of Audible Signals

In all the countries employing ATSs, many signals have been tried and used to aid impaired pedestrians, and while some were successful, others were not. In general, signals whose sounds can easily be confused with that of the surrounding environment have been refused by visually impaired pedestrians. Some of the used tones include buzzing, beeping and bird calling sounds such as the 'cuckoo' and 'peep-peep'. The latter two have been standardized by the Transportation Association of Canada (TAC) in 1992 to be used in ATSs for crossing North-South and East-West respectively. Some studies have been carried out to introduce new signals and compare their performance with the old ones. From these studies, those proposed by Giguére et al. (2003), and Laroche et al. (2000), were most relevant.

Laroche et al. (2000) considered four different signals, including the 'cuckoo', 'peep-peep', 4-note melody and a 'neo cuckoo' signal played an octave lower than the original 'cuckoo'. The study had three main phases to measure the performance of these four signals – measuring alignment within a simulated pedestrian corridor with signals emitted simultaneously at both ends of the corridor, measuring alignment within a simulated pedestrian corridor with signals emitted alternating from both ends, measuring alignment in a busy intersection. Of these the third one was postponed to a future study.

The study consisted of evaluating the performance based on three different measures viz., the difference between the center line & the point of arrival; the root mean square (rms) average distance between the center line & the actual path; and the crossing times. The effect of changing the four signals, the alternating mode and the three departure orientations on the above measures was studied using a multivariate analysis of variance (MANOVA). A subjective questionnaire was carried out in the end of the experiments involving the level of signals, sound quality, ease of sound source location and the degree of confidence gained from the signals while crossing. The results of both the statistical tests showed that the 'peep-peep' obtained the largest deviation value and that the alternating mode gave better results regarding the crossing duration and the rms average deviation. The subjective questionnaire showed that the melody signal was judged as the most acceptable and the 'peep-peep' signal as the worst.

The second study proposed by Giguére et al. (2003) was a continuation of the above discussed study. In this, the authors carried out a study on six different signals to find out which were easiest to localize and which were judged the safest. The six signals tested included the ordinary 'peep-peep' and 'cuckoo' signals standardized by the TAC plus four variations of the melody signal proposed by the Institute Nazareth et Louis-Braille (Longueuil, QC). The six signals were judged based on mode of operation, choice of melody and sound intensity. Table 2.1 displays the six different signals used and their acoustic description.

Table 2.1: Six tones used for ATSs and their acoustic description

Signal	**Description**
1.Cuckoo	Consists of a sequence of 2 complex sounds, with durations of 70 and 140 ms and fundamental frequencies of 1100 and 900 Hz respectively, and with a pause in between of 200 ms. Each contains harmonics of the fundamental up to 8000 Hz and with harmonics decrease level of 6 dB per harmonic. The signal is repeated every 1.5 seconds.
2.Peep-Peep	Sounds like a bird chirp with a downward frequency sweep between 4200 and 1900 Hz for the fundamental, and 8400 and 3800 Hz for the second harmonic. It has duration of 140 ms and is repeated every 1 second.
3.Signal 3 (Original Melody)	Consists of a continuous sequence of 4 notes, each lasting for 300 ms and with fundamental frequency of 1325, 1125, 1000 and 900 Hz respectively. A third harmonic is present for each tone at a level 6 dB lower than the fundamental. The melody lasts for 1.2 seconds.
4.Signal 4	Similar to 3, except that possible harmonic components are included for each note up to 8000 Hz. The decrease level in successive

	harmonics is 3 dB. It also reflects a richer harmonic content.
5.Signal 5	Signal 4 played one octave lower.
6.Signal 6	Signal 5 with a decrease in notes duration to 250 ms and a pause of 50 ms between notes.

After defining these signals, the authors carried out experiments on 19 subjects in the middle of a dead-end street to perform a quantitative and qualitative evaluation of the signals. The qualitative evaluation was based on the subjective appraisal given by each subject on the different signals. This was based on two appraisal measures, an individual appraisal based on sound quality, intensity level, ease of localization and the level of safety brought by each signal; and a relative appraisal calculated on a 0 to 100% scale comparing the signals to each other. Both the individual appraisals and the relative appraisal showed a significant difference between signals 2 and 3 and the other signals, with the former signals having a lower appraisal value except for the signals 5 and 6 which had higher relative appraisal values. Finally, the authors concluded that with respect to the standardized 'peep-peep' and 'cuckoo' signals, the latter had a higher efficiency and that the proposed signals 5 and 6 offered superior localization performance and subjective appraisal scores compared to the other signals.

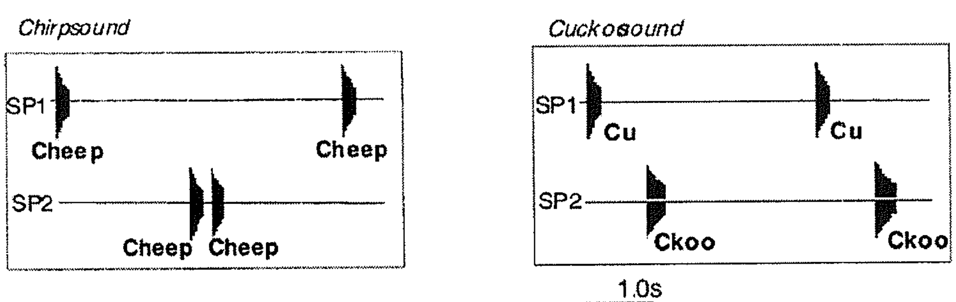
Bentzen et. al. (2004), conducted a survey on speech messages for accessible pedestrian signals. Initially they developed sample walk and pushbutton information messages that were applicable to different intersection geometries and signalization patterns and were variable in message content, length and structure. Then the messages that were judged by most members of the panel to be unambiguous and to clearly convey the minimum necessary information were developed into a survey instrument for obtaining data on preferences for message content and structure. Their survey also contained items to evaluate message comprehension. The survey was mailed to 160 stakeholders who were not visually impaired. In addition, it was administrated in Braille, in large print, or orally to 170 pedestrians with visual impairments. Survey results served as bases in developing a recommended practice for the structure and content of walk messages and pushbutton information messages for push button-integrated ATSs.

In one of the recent studies about the types of ATS signals, Williams et. al. (2005) studied the effects of two types of ATSs on the street crossing behaviors of 24 totally blind participants. One of the ATSs used a sound generator and vibrating hardware that were integrated into the pedestrian push button. This signal was heard from a certain distance very near to the push button and a different message or repetition rate was used to indicate the walk interval. The second ATS used a pulsing LED to illuminate the message in the pedestrian signal head which then transmits a message to a handheld receiver carried by the blind traveler. Finally depending upon the variable tones, the handheld receiver provided a walk or wait message, which was audible only to the user. Data was collected on crossing speed, the duration between the start of the walk and entering the crosswalk, the number of cycles missed, and the accuracy of the crossing. Finally they concluded that the duration to start crossing and the crossing time to cross the street was significantly shorter when participants used the handheld device than when they used the audible push-button device. Moreover the number of missed cycles was significantly lower when the participants used either of the ATS devices than when the participant crossed without an ATS device. However, there was no difference in the number of missed cycles between both the ATS devices.

2.3 Operation Modes

Tauchi et al. (1998) conducted a study in which three sound patterns were tested – a simultaneous sound pattern, an alternating pattern using the same sound and an alternating pattern using different sounds. They carried out three experiments. In the last one, they compared the performance of the alternating pattern using the same sound and the alternating pattern using different sounds. Twelve blindfolded and one visually impaired volunteer carried out the experiment. The experiment itself was carried out in a parking lot, where two speakers were placed 20 meters apart at 2.4 meters above the ground. The subjects were asked to walk the distance between the speakers and to lift their hand if they experienced any difficulty in differentiating between the front and rear speakers. Again, the results showed that the alternating pattern using different sounds achieved better results and that subjects were always able to identify the sound source along the entire crosswalk using this pattern.

Another study to consider the operation mode was done by Ono et al. (1999). In this study the authors used simulated bird sounds as signals in this study, namely the ‘chirp’ and the ‘cuckoo’ sounds plus a new pattern of alternating (back-and-forth) signals. In this pattern, two different sounds were emitted from each end speaker. Figure 2.1 shows how this pattern works with the two different sound signals. Again, the authors believed that under this pattern, pedestrians could more easily distinguish between the sounds coming from the front and rear speakers. The experiment was carried out in a busy intersection in Japan where a 25 meters wide road with two lanes of traffic in each direction intersected with another 12 meters wide. The 'chirp' signal was used in the North-South direction while the 'cuckoo' was used in the East-West direction. The speakers were installed at the center of the crosswalks, 3 meters high and an axial inclination of 45 degrees to the ground. The experiments were carried out with the help of seven volunteers who took the tests and completed a quick questionnaire about their orientation while crossing the street. All but one indicated that it was easier to orient themselves to the correct direction before crossing and to confirm their position while crossing due to all four speakers emitting different sounds. Only one participant indicated that he was not very confident about the sound source.



SP1: Speaker # 1, SP2: Speaker # 2

Figure 2.1: Alternating Pattern with Different Sounds Ono, H. (1999)

Laroche et al. (2000) measured the alignment of pedestrians under two ATS operation modes, the simultaneous and the alternating mode. In the former, signals were emitted from the two end speakers (North and South or East and West speakers) simultaneously. Some previous experiments showed that under this operation mode, pedestrians seemed to loose their orientation at the midway point as they did not know whether the signal they were hearing was coming from the speaker in front or behind them. This issue has driven researchers to try new modes; one such example is the alternating mode. Under this mode, signals are emitted in an alternating fashion between the two end speakers. This has been believed to reduce the amount of confusion experienced by the impaired pedestrian.

In a study conducted by Ashmead et. al. (2004) a systematic investigation of the effects of variations in loudspeaker locations on identifying which crosswalk has the audible walk signal was performed. For this study, participant groups comprised eight sighted, blindfolded adults and six totally blinded adults aged 27 to 42 and 27 to 65, respectively. A mock 90-degree four-leg intersection with 16-meter-long crosswalks was laid out in a parking lot. Commercial APS ped-head mounted devices were positioned 2.44 meters high on tripods to simulate pedestrian signal heads. Each corner provided a different arrangement of devices to investigate the effect of typical placements on pedestrian's ability to tell which crosswalk had the walk signal. Three different signal modes were used: simultaneous, with the signals from both ends of a crosswalk sounding concurrently; alternating, with signals presented alternative from each end; and with the signal presented only from the far end of the crosswalk relative to the pedestrian. Each participant was tested on a single block of six trials. Results indicate that both the positioning of loudspeakers and the mode of signal presentation influence the accuracy of judgments about which crosswalk has the walk signal.

Noyce and Bentzen (2005) studied on the duration of holding the ATS push button pressed to activate the tones or information message features. They developed a time distribution of typical pedestrian push-button activation durations after obtaining the data by attaching a voltage recorder to the pedestrian push-button circuit inside the traffic signal controllers. This device recorded the amount of time, to the nearest 1/100 of a second that each pedestrian push button was pressed. A total of 1,439 push-button presses were recorded at eight locations in three cities in Wisconsin and Massachusetts. The average push-button press duration was 0.2 s. Most of the push-button presses recorded were less than 1.0 s except four which exceeded 3.0 s. Their results show that the duration of holding the push button pressed to activate the tones or obtain additional crossing information can be reduced to approximately 1 s without a significant number of false calls. Finally they concluded that a 1.0 sec. press will minimize the effort required for pedestrians to activate special accessible features, while it will minimize unnecessary noise and vehicular traffic disruption.

Another study was undertaken by Bradley and Dunlop (2005) who investigated on way-finding directions for the visually impaired pedestrians. They aimed to study whether a group of sighted participants and that of visually impaired participants, experience a difference in mental and physical demands when given two different sets of verbal instructions directing them to four landmarks. The first set of instructions was the route descriptions as portrayed by sighted people and the second set was route descriptions as portrayed by visually impaired people. Their objective was to measure the time taken by participants to reach landmarks and the number of deviations that occurred. A work load index questionnaire provided an indication of participants' subjective perception of workload. The results revealed that instructions as portrayed by the visually impaired people resulted in a lower weighted workload score, less minor deviations, and quicker times for visually impaired participants. The sighted group, on the other hand, witnessed that these instructions were found to cause a higher weighted workload score. They concluded that visually impaired people rate their level of workload less when messages have a reduced amount of textual area/street based information, and incorporate sensory, motion, and social contact information.

2.4 Pedestrian orientation and behaviour

In a research conducted by Bechtel et. al. (2004) in the City of Oakland, California a scramble signal was implemented at the intersection of 8th Street and Webster Street to determine whether the installation of the pedestrian scramble at this location increased pedestrian safety. Scrambles are a type of traffic signal that give pedestrians exclusive access to an intersection by stopping vehicular traffic on all approaches, allowing pedestrians to cross diagonally or conventionally. The analysis was conducted on pedestrian-vehicle conflicts and pedestrian violations occurring at the intersection before and after the signal was modified, and pedestrians were surveyed to ascertain public attitude toward and comprehension of the change. Their findings demonstrated a significant decrease in the rate of pedestrian-vehicle conflicts at the target intersection after the pedestrian-scramble phasing was implemented. However, their findings also demonstrated an increase in the number of pedestrian violations after implementation of the scramble, especially during the Saturday midday observation period due to the weekend attractions. They finally concluded that the scramble has reduced the number of pedestrian-vehicle conflicts at the intersection, although it has increased the instances of pedestrian non-compliance during the time periods observed.

Wall et. al. (2004), conducted three experiments to investigate how characteristics of signal presentation affected usefulness of the auditory signal for guiding the crossing behavior. In this survey blind and blindfolded sighted adults crossed a simulated crossing with recorded traffic noise to approximate street sounds. Crossing was more accurate when signals came only from the far end of the crossing rather than the typical practice of presenting signals simultaneously from both ends. Alternating the signal between ends of the crossing was not helpful. Also, the customary practice of signaling two parallel crossings at the same time drew participants somewhat toward the opposite crossing. Providing a locator tone at the end of the crossing during the pedestrian clearance interval improved crossing accuracy. These findings provide a basis for designing audible pedestrian signals to enhance directional guidance.

Virtual Acoustics is one of the interesting areas of study in sound engineering. Ito et. al. (2005) are developing an environment, in which pedestrians hear a car crossing in front of them and judge the right time to cross a driveway. They conducted a preliminary experiment to demonstrate that the reverberation and reflection of sound is an effective way of judging the arrival time of car. Ten sighted subjects were asked to listen to a car passing by them in the virtual acoustic environment and press a computer button when they perceived the car passing in front of them. The results of their study suggested that reverberation and reflection of sound is useful for the visually impaired pedestrians in identifying the right time to cross driveways safely. Such findings obtained from the psycho-acoustic experiments will be very useful to develop education and rehabilitation programs at the school for the blind.

Scott et. al. (2005) investigated the effects of push-button placement and the type of crossing tones (or "Walk" signal) on visually impaired participants' ability to determine which of two streets had the "Walk" signal. The subjects in his experiments performed this task most quickly and most accurately when each push-button-integrated ATS was mounted on its own pole. The poles were placed along the outer line farthest from the center of the intersection of the associated crosswalk and each pole was located within a few feet of the curb. The crossing tone from each ATS was a fast tick percussive sound at 10 repetitions per second. They concluded that where two push buttons are installed on a single pole, verbal messages indicating to cross the street, resulted in greater accuracy than two different sounds (fast tick and cuckoo) to indicate the two crossings.

Rouphail et. al., (2005), conducted a study to analyze the acceptance behavior for both sighted and blind pedestrians near roundabouts and to integrate that behavior into a microscopic simulation model of pedestrian and vehicular traffic operations at a roundabout. The basic idea behind this process was to quantify the mutual impact of pedestrian crossing behavior on vehicle operation, and vice versa. The process also allowed them to evaluate various pedestrian treatments at the roundabout. The simulation results indicated that pedestrian delay increases in a nonlinear fashion as vehicle volume increased. Moreover, they noticed a small difference between the sighted pedestrian and blind pedestrian delays at the entry and exit legs; the latter having a higher delay on the exit side. They concluded that placing a pedestrian-actuated, signalized crossing at the roundabout results in delays to blind pedestrians that are comparable to those experienced by sighted pedestrians that cross at the un-signalized splitter island.

2.5 Modern devices and the recent developments

Hughes et. al. (2000) evaluated whether automated pedestrian detectors would result in fewer overall pedestrian–vehicle conflicts and fewer inappropriate crossings when used in conjunction with standard pedestrian push buttons. Automated pedestrian detection systems not only detect the pedestrians approaching the curb and call the Walk signal, but also extend the clearance interval in order to allow slower persons to finish crossing. Hughes et. al. video recorded the data at intersection locations in Los Angeles, Phoenix and Rochester. Their results indicated a significant reduction in vehicle-pedestrian conflicts, as well as a reduction in the number of pedestrians beginning to cross during the Don’t Walk signal. There were very minor differences between microwave and infrared detectors. Detailed field testing of the microwave equipment in Phoenix revealed that fine-tuning of the detection zone is still needed in order to reduce the number of false calls and missed calls. They concluded that the automated pedestrian detectors can provide significant operational and safety benefits when installed in conjunction with conventional pedestrian push buttons at actuated traffic signals. The likelihood of fewer inappropriate crossings (during the steady Don't Walk signal) and fewer vehicle-pedestrian conflicts is expected to be correlated with improved pedestrian safety.

Ross and Blasch (2000) developed three wearable orientation interfaces and evaluated toward this purpose: a stereophonic sonic guide, speech output and shoulder-tapping system. Street crossing was used as a critical test setting in which to evaluate these interfaces, the shoulder-tapping system was found most universally usable. The authors concluded that a combined tapping/speech interface would provide usability and flexibility to the greatest number of people under the widest range of environmental conditions based considering the great variety of co-morbidities within this population,

Crandall et. al. (2001) studied on three problems that are among the most challenging and dangerous faced by blind pedestrians, viz., negotiating complex transit stations, locating bus stops and safely crossing the traffic intersections. They reported the results of human factors studies using a remote infrared audible sign system (RIAS), Talking Signs(R), in these critical tasks, examining issues such as the amount of training needed to use the system, its impact on performance and safety, benefits for different population subgroups and user opinions of its value. They presented the results in the form of objective performance measures and in subjects' ratings of the usefulness of the system in performing these tasks. Findings are that blind people can quickly and easily learn to use remote infrared audible signage effectively and that its use improves travel safety, efficiency and independence. It was also found that Talking Signs at intersections significantly improved safety, precision and independence in street crossing for independent blind travelers who use a long cane or guide dog, or those with mild to moderate hearing loss. Use of the Talking Signs system at intersections appears likely to decrease the probability of crashes between vehicles and pedestrians who are blind. Orientation is improved by provision of unambiguous and definitive information about location and immediate destination, so the anxiety associated with disorientation is also decreased. Finally they concluded that remotely readable infrared signage technology such as the Talking Signs system can be helpful to blind and visually impaired persons in a number of commonly encountered situations that normally pose major problems for them.

Tzovaras et. al. (2002) presented the virtual reality applications developed for the feasibility study tests of the VR training system that allows visually impaired people, to study and interact with various virtual objects. A number of custom applications have been developed based on the interface provided by the Cyber Grasp hepatic device. Eight test categories were identified; the corresponding tests were developed for each category and were tested with twenty-six blind persons. The evaluation results showed that the end users participating in the tests faced no general usability difficulty to the pilot system and little or no guidance was needed by the participants at all. On the contrary, they enjoyed completing their tasks and showed a lot of commitment. The overall result was that the prototype introduced was considered very promising and useful. Moreover the approach chosen fully describes the belief of blind people to facilitate and improve training practices and to offer access to new employment opportunities.

Ross and Blasch (2002) continued their study done in 2000 a series of indoor and outdoor experiments using a variety of technologies and interfaces. They developed and evaluated three wearable orientation interfaces: a virtual sonic beacon, speech output and a shoulder-tapping system. Street crossing was used as a critical test situation to evaluate these interfaces. The shoulder-tapping system was found most universally usable. Results indicated that, from a great variety of pedestrians within this population that comprises of mostly older persons, optimal performance and flexibility may best be obtained in a design that combines the best elements of both the speech and shoulder-tapping interfaces.

Loomis et. al. (2005) conducted a study of route guidance using a navigation system that receives location information from a Global Positioning System (GPS) receiver. In this study fifteen visually impaired participants traveled along 50-meter paths in each of five conditions that were defined by the type of display interface used.

Table 2.2: Five conditions in a route guidance system using GPS [Loomis et. al, 2005]

			Type of Display		
Features	Virtual speech	Virtual tone	HPI tone	HPI speech	Body pointing
Auditory source	Headphones	Headphones	Shoulder-mounted speaker	Shoulder-mounted speaker	Shoulder-mounted speaker
Compass location	Head	Head	Handheld pointer	Handheld pointer	Torso
Nonspeech acoustic signal	None	Tone (5 per second); swept tone (2.3 per second)	Tone (5 per second)	None	Tone (5 per second)
Acoustic off-course indicator	None	Yes; type of tone	Yes; tone if pointer is accurate; bearing if off by more than 90 degrees	Speech; straight left/right bearing if off by more than 90 degrees	Yes; tone if pointer is accurate; bearing if off by more than 90 degrees
Acoustic directional spatiali-zation	Yes	Yes	None	None	None
Acoustic distance spatiali-zation	Intensity	Intensity	Intensity	None	Intensity
Haptic pointer	None	None	Handheld	Handheld	Torso

The results showed that all the 15 participants were able to complete all tests with a mean travel distance of only 62 meters and a mean travel time of 110 seconds which implies that the technology has a promise for guiding the visually impaired pedestrians precisely through space when precise GPS data are available. In comparing the performance and subjective assessments of the different displays, the virtual-speech display provided continually updated information on the distance to the next waypoint, whereas the other displays provided this information only every 8 seconds. The subjective evaluations indicated that the participants judged virtual speech to be the best, but part of the reason was the availability of information about the distance to the next waypoint. The next-best option was body pointing, which was judged better than both the HPI-speech and the virtual-tone displays

.

Figure 2.2: A pedestrian wearing the Personal Guidance System that receives location information from a GPS receiver [Loomis et. al., 2005]

Ross and Lightman (2005) developed a computing network to assist persons with vision loss in finding their way around buildings and other indoor public spaces. It is based on the idea that tiny solar-powered digital chips can be used to store relevant pieces of information that can be placed along building walkways like a trail of crumbs to follow. A wireless network of crumbs provides access from any point in the building to a central server that provides orientation and way-finding information. The participants in this study felt that the prototype was superior in terms of its ability to enhance their mobility performance based on their effort and the time expended. Further, they felt the prototype was easy to understand & use, intuitive and gave them the information they needed.

Gaunet (2006) proposed functional specifications for a localized verbal way-finding aid for blind pedestrians, in simple and structured urban areas which relied on specific database features and guidance functions such as instructions and spatial information provided at specific places. She conducted an experiment with seven pedestrians using cane and three pedestrians who used dogs. In this experiment requirements for simple & structured urban areas and for complex & unstructured urban areas were tested. Gaunet found a few hesitations and errors along with the need for few modifications of the verbal guidance rules and for a one-meter localization device for traversing crosswalks.

2.6 Studies related to ATS location & design

Laplante and Kaeser (2004) studied on the standards used for the pedestrian walking speed versus the street widths. As per the Manual on uniform traffic control devices (MUTCD) a normal walking speed 4.0 ft (1.2 m) /sec. is specified as the design speed for the pedestrian clearance interval including the 'don't walk' flashing phase and slower speeds are suggested only for special situations in which an unspecified number of elderly pedestrians are expected to cross. They noted that in some cases, many slow pedestrians are not able to complete their crossing before opposing traffic is released. Addressing this concern, the authors recommended that MUTCD should use a 3.5 ft./sec. minimum walking speed for walking from curb to curb for determining the pedestrian clearance interval and a 3.0 ft/sec. walking speed across the total crossing distance for the entire walk plus pedestrian clearance signal phasing. In any case, the minimum walk signal indication still should be 4 sec. A summary of pedestrian timing comparison and analysis is shown in table 2.

Table 2.3: Analysis done by Laplante and Kaeser on the pedestrian crossing timing

Table 1. Pedestrian clearance times.

Street width	4.0 ft. (1.2 m)/sec.	3.5 ft. (1.1 m)/sec.	3.0 ft. (0.9 m)/sec.
40 ft. (12 m)	10.0 sec.	11.4 sec.	13.3 sec.
60 ft. (18 m)	15.0 sec.	17.1 sec.	20.0 sec.
80 ft. (24 m)	20.0 sec.	22.9 sec.	26.7 sec.
100 ft. (30 m)	25.0 sec.	28.6 sec.	33.3 sec.
120 ft. (36 m)	30.0 sec.	34.3 sec.	40.0 sec.

Table 2. Total pedestrian time (minimum).

Street width	4.0 sec. walk + 4.0 ft. (1.2 m)/sec. pedestrian clearance time	4.0 sec. walk + 3.5 ft. (1.1 m)/sec. pedestrian clearance time	4.0 sec. walk + 3.0 ft. (0.9 m)/sec. pedestrian clearance time	3.0 ft. (0.9 m)/sec. total pedestrian time – 3.5 ft. (1.1 m)/sec. pedestrian clearance time = walk
40 ft. (12 m)	14.0 sec.	15.4 sec.	17.3 sec.	15.4 – 11.4 = 4.0 sec.
60 ft. (18 m)	19.0 sec.	21.1 sec.	24.0 sec.	22.0 – 17.1 = 4.9 sec.
80 ft. (24 m)	24.0 sec.	26.9 sec.	30.7 sec.	28.7 – 22.9 = 5.8 sec.
100 ft. (30 m)	29.0 sec.	32.6 sec.	37.3 sec.	35.3 – 28.6 = 6.8 sec.
120 ft. (36 m)	34.0 sec.	38.3 sec.	44.0 sec.	42.0 – 34.3 = 7.7 sec.

** Note: 3.0 ft. (0.9 m)/sec. total pedestrian time is based on street width plus an assumed ramp length of 6 ft. (1.8 m).*

Stollof (2005) conducted a workshop jointly with the ITE and the US Access Board in October 2004 where in the participants were proposed to develop design schemes for intersections with curb radii of 10 feet, 25 feet, 30 feet and 40 feet. The basic idea behind this exercise was to make the intersections / crosswalk designs comprehensible especially by the visually impaired pedestrians by enhancing curb ramp orientation, edges and other features that might carry directional or travel content. By the end of the workshop participants noted that design for pedestrian use should focus on key users such as children, older walkers and pedestrians who have disabilities, particularly those who have vision loss.

Markowitz et. al. (2006) studied the impacts of the popular devices on collisions, pedestrian behavior & attitudes, motorist behavior and signal maintenance needs. It was noted that the number of pedestrian injuries declined by 52% after the introduction of the countdown signals. Moreover the countdown reduced the proportion of pedestrians finishing crossing on the red and did not result in an increase in drivers running red lights. The devices did not appear to reduce effectiveness or trigger public complaints. Infact they were viewed very favorably by the pedestrians for providing additional information and for being easily understandable.

2.7 Conclusions

From what has been discussed in the past sections, the following conclusions can be made regarding ATSs, their signal sounds & modes of operation, pedestrian orientation & behavior and ATS design recommendations.

1. With regard to basic signals, the performance of the 'cuckoo' signal is always better than that of 'peep-peep' signal.
2. With regard to melody signals, those with lower frequency and richer in harmonics seem to perform better as suggested by Giguere et. al. (2003).
3. Push button holding time to activate the ATS tones will affect the pedestrian performance as studied by Noyce and Bentzen (2005). It has been noted in their survey that longer push button holding time had resulted in the increase in the false calls.
4. In general, melody signals have higher efficiency than the ordinary beeping signals.
5. Alternating signals are more reliable and easier to distinguish than simultaneous signals. Furthermore, alternating pattern signals with different sounds are even more efficient than those that emit the same sound.
6. The positioning of loudspeakers and the mode of signal presentation influence the accuracy of judgments about the walk signal as studied by Ashmead et. al. (2004).
7. The minimum pedestrian walking speed to be used while designing ATS systems or setting the crossing time duration should be 3.5 ft/sec as recommended by Laplante and Kaeser (2004).
8. Virtual reality plays an important role in training the blind pedestrians about new system as suggested by Tzovaras et. al. (2002).

Therefore, an optimum ATS would be one that employs melodies with low frequencies and rich harmonics in an alternating pattern using different sounds. As it has been noted from the above survey, a very wide variety of factors has been taken into consideration by various authors in aiming research. Several approaches have been presented involving various components of an ATS system. However, the proposed research has its own exclusivity. The factors considered in this approach were never discussed earlier and its results and conclusions are based on realistic studies conducted in the actual environment. It was believed that studies whose conclusions were based on theoretical evaluations or through artificial set-ups differ from the real world. Hence the proposed approach aimed at doing a realistic study through data drawn from real and live traffic intersections in the city.

In this study, three main experiments were designed at each intersection considering various factors such as speaker height, activation system, seasons, street width and complexity. During the course of experimentation, based on the subjects' comments, the factor 'speaker height' has drawn more attention. Hence a detailed analysis was done using the Analysis of Variance at varying the levels of the speaker height to investigate its effects on the system and its interaction with other factors in the system.

CHAPTER 3

DESIGN OF EXPERIMENTS

3.1 Introduction

Design of Experiments is widely used in research, commercial and industrial settings for different purposes. The primary goal is usually to extract the maximum amount of unbiased information about the factors affecting a process from as few observations as possible [Montgomery D.C. 1997]. In research and development, often half of the resources are spent on solving optimization problems. With the rapidly rising costs of conducting experiments, it is essential that the optimization is done with as few experiments as possible. This is one important reason why design of experiments is needed and is finding increasing use in manufacturing to optimize the production process. The design of experiments (DOE) was first introduced in the early 1920s when a scientist at a small agricultural research station in England, showed how one could conduct valid experiments in the presence of many naturally fluctuating conditions such as temperature, soil condition, and rainfall. The design principles developed for agricultural experiments have been successfully adapted to industrial and military applications. Genechi Taguchi in late 1940's spent considerable effort to make this experimental technique more user-friendly by carrying out significant research with these techniques and applying them to improve the quality of manufactured products. His method is popularly known as the Taguchi method or Taguchi approach which is one of the most effective quality building tools used by engineers in all types of manufacturing activities today.

In an experiment, one or more process variables (or factors) are deliberately changed in order to observe the effect the changes have on one or more response variables. The statistical design of experiments is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. While in the application of science, analysis of variance (*ANOVA*) techniques are used to uncover the interactive nature of reality, as manifested in higher-order interactions of factors, in industrial settings interaction effects are often regarded as a nuisance which are of no interest; they only complicate the process of identifying important factors. Quality professionals use DOE to identify the process conditions and product components that influence quality and then determine the input variable settings that maximize results.

In this research, the principals of Experimental design have been applied to evaluate the statistical significance of an effect that a particular factor exerts on the dependent variable of interest. This chapter outlines the research method, the factors considered for designing the experiments, the subjects involved, the equipment used and the procedure adapted for conducting the experiments.

3.2 Research Method

Four traffic intersections in the city that are unique to each other are selected for experimentation. A set of three experiments have been designed to do a real-time testing on the current signal systems at live intersections with the help of the blind pedestrians who volunteered for this project.

The most appropriate approach to study the factors in an experiment would be to vary the factors of interest in a full factorial design, that is, to try all possible combinations of settings. In this study, as there were maximum 4 factors in any experiment, the number of observations needed would be $2^4 = 16$. Hence, sixteen subjects were selected which randomly included 9 female and 7 male volunteers, classified as legally blind based on criteria for registration at the Canadian National Institute for the Blind (CNIB). The CNIB standard classifies a person as legally blind if their central acuity does not exceed 20/200 in the better eye with correcting lenses or whose visual acuity if better than 20/200 has a limit to the central field of vision of no greater than 20 degrees. This means that even when wearing glasses, the best that can be read is the 20/200 line on the eye chart (usually the top "E") from a distance of 20 feet with your better eye. Or, have tunnel vision with a visual field less than 20 degrees [Consolidations regulations of Canada 1978, chapter 371]. All participants were accustomed to crossing independently at signalized intersections using a long cane or a guide dog.

In order to have the volunteers participate in the testing, approval was granted by the Ethics committee at the University of Manitoba. As part of the agreement, all volunteers had to sign a consent form (refer to Appendix 1) assuring their anonymity throughout the project and informing them that the purpose of the experiments was to identify the best available ATS technology that meets community usability needs. They were also informed that they would need to approach the ATSs and cross the streets several times to obtain information on the ATS performance at various locations in use by the City of Winnipeg.

The following setting was used in all the experiments that were conducted. Two audible traffic signal speakers that gives out Chirp tone & Cuckoo tone for locating and crossing and tick tone for activation installed on the poles at heights of 4 feet and 10 feet from the ground, the 'WALK' indication of a walking person (standard pedestrian symbol) in all cases, the 'DON'T WALK' indication of an upraised hand, a video camera to record all the tests.

To simplify the testing, four intersections whose streets are right angled to each other were considered for testing. Each of the intersections possessed a unique property that differed from others, allowing for direct comparisons of each variable. For example the number of lanes varied from 4 x 4 (4 lanes in each direction) up to a much larger 8 x 4 configuration with or without medians; the surroundings varied from none to large high-rise buildings; and the activation system. Refer table 3.1.

Table 3.1: The four intersections used in the experiments

Intersection	**Lanes**	**Median**	**Surroundings**	**Activation System**
Donald & York	4x4	No Median	None	Non-Push Button
Smith & York	4x4	No Median	High-rise Buildings	Non-Push Button
Broadway & Fort	8x4	Median	High-rise Buildings	Push Button
Worthington & St. Anne's	6x2	Median	None	Push Button

Testing consisted of two major phases – Pole Location and Street Crossing which were necessary to analyze how speaker height affected the performance of the locating, activating and crossing tones.

- **Phase 1: Locating tone**

At the beginning of the experiments, the volunteers were instructed to start a half block away from a corner of the intersection and attempt to locate the pole using their own method with the help of either the locating tone or the crossing tone. As these experiments were done in real traffic at live intersections, a person was designated to follow the volunteers at a close enough distance to protect them but far enough not to distract them. To maintain a consistency in the subjects' orientation of the intersection and their feedback, all subjects had a similar starting point at all intersections, i.e. half block away from the south-east corner of each intersection. In this phase, the volunteer did not cross the street because the objective was to test the ease of locating the push button pole. After finding the pole, the subjects were instructed to activate the crossing tone via push button, where applicable.

- **Phase 2: Crossing tone**

In this phase, the volunteers have to cross the street with the help of the activated crossing tone. As in the previous phase, the designated person will follow them at a close enough distance to ensure the safety of the volunteers. As an indication of their decision to cross the intersection, the volunteers raised their hand right before crossing the street for the designated person to notice them. If the volunteers lose their orientation during the crossing process or are taking an incorrect decision, the designated person will warn them and will assist them to cross the street to a safe location. This procedure was repeated until the north-south and east-west directions were fully traversed. Figure 3.1 above shows the path taken by each volunteer when traversing the intersection and figure 3.2 shows one of the volunteers crossing the street with the help of a guide dog while being recorded on the video.

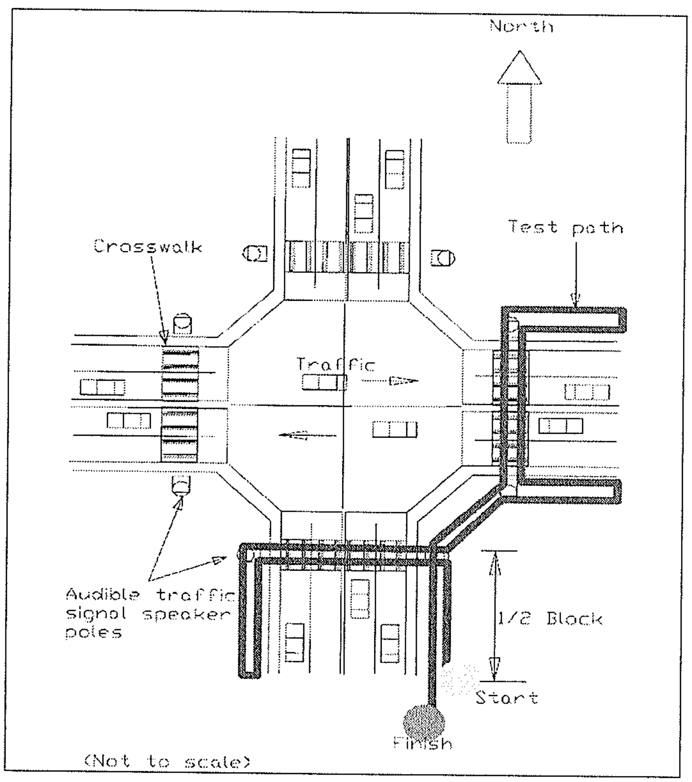


Figure 3.1: The path taken by each volunteer when traversing the intersection

Figure 3.2: One of the volunteers crossing the street with the help of a guide dog

At the end of the experiments, the volunteers were asked questions concerning the whole experience of locating & crossing the intersection and their answers were recorded in the designed data sheet. All the tests were done outdoors and data was collected simultaneously 4:00 pm and 7:00 pm on weekdays to replicate the typical conditions during the peak traffic hours. The volunteers were also encouraged to make any comments they wish concerning any part of the experiment. The experiments are also recorded using a video camera but it is not planned to publish or show those video tapes to anyone except the principal investigator and the assistants involved in the analysis and system design process.

The questionnaire contained questions focusing on the topics of locating tone, activation system and crossing tone, using a 1-10 rating system for each response. At the end of each questionnaire, the volunteers were also encouraged to share any general comments they had about the intersection. The data was then collected in both seasons by repeating the whole experiment with each subject at all four intersection by changing the speaker height from 10 feet (3.05 m) to 4 feet (122 m). Thus the total observations noted for all the sets of experiments is *Two Seasons* multiplied by *Four intersections* multiplied by *Two speaker heights* multiplied by *the number of volunteers* which varied between 8 to 11 in each experiment as all 16 volunteers were not available for all the experiments. Therefore the total number of observations will be 2 x 4 x 2 x volunteers = 16v = 161 (approx.). Finally the collected data was compiled in a spreadsheet and fed to the statistical software MINITAB® to do the analysis of variance (ANOVA).

3.3 Considered Factors

Detailed description of all factors and the basis on which the experiments are done are as follows.

Season (S):

As Winnipeg's climate changes drastically from winter to summer, it seemed logical to assume that weather might in some way affect the functionality of the audible signal system. This factor is to compare the results from data taken in different seasons and to see if there is any effect of weather on the audibility of the speaker tones. The two values considered for this factor are 'Summer' and 'Winter'.

Speaker height (SH):

This factor is selected based on a generalized idea in mind that the higher the source of sound the weaker will be its audibility to a pedestrian at the ground level.

This factor was very helpful to compare the data taken using speakers installed at different heights. The two values considered for this factor in this experiment are '4 feet' and '10 feet'. As one can notice, this is the factor that was emphasized more in the entire study.

Activation System (AS):

As mentioned earlier there are two kinds of activation systems available in the City of Winnipeg. These are Push button system (PB) and the Non-push button system (Non-PB). It was important to find out which system will outperform the other. As a result, a direct comparison of the two levels the push button and non-push button systems was performed.

Intersection Size (Lanes):

As speaker intensity is known to decrease with distance, Intersection complexity was considered an important variable for this project. Complexity can be defined by several features such as the 'street width', 'existence of median', 'number of streets converging to an intersection', 'the surroundings' and 'number of lanes'. Out of all these, the number of lanes is deemed important because the street width and the existence of median are considered to be directly dependant on the number of lanes.

Many intersections within the city require considerably more effort to traverse due to the existence of medians. This is especially true for visually impaired pedestrians using the audible signal system, as many large intersections with medians require the ATS system to be activated twice to cross the street, first at the crossing point and again the median. For example to cross Broadway from

South to North, the ATS must be activated by the push button located at the South end and again it needs to be re-activated upon reaching the median to cross the street from the median to the North end. Due to the existence of such situations, Intersection Complexity was deemed an important variable to be considered in these tests. The following table gives a list of all the intersections considered for this study and summarizes the complexity of each intersection.

High-rise buildings (HR):

Several audible signal equipped intersections in the city are surrounded by high-rise buildings, resulting in the potential for echoing effects. Since the audible signal system requires the pedestrian to be able to sense the direction of the sounds emitted by the speakers, it seems quite possible that the effect of echoes could have an impact on the system's performance. As a result, Intersection Surroundings was selected as one of the considered variables for these tests. Another goal was to study the interaction effect between this factor and the other considered factors.

3.4 Design of Experiments

After a careful review of the problem, a plan is developed, the main factors are selected and finally three experiments have been designed. The first experiment is done to analyze the performance of locating tones. The second and third experiments are done to analyze the audibility and the duration of the crossing tones respectively. Table 3.2 gives a list of the three experiments designed and the factors considered.

Table 3.2: Summary of the design of experiments

Experiment	Factors	Levels
Experiment 1: Locating tone audibility	Seasons	Summer, Winter
	Speaker height	10 ft., 4 ft.
	Push button	Yes, No
	High-rise buildings	Yes, No
Experiment 2: Crossing tone audibility	Seasons	Summer, Winter
	Speaker height	10 ft., 4 ft.
	High-rise buildings	Yes, No
Experiment 3: Crossing tone duration	Seasons	Summer, Winter
	Speaker height	10 ft., 4 ft.
	No. of Lanes	2, 4, 6, 8

Locating Tones

The purpose of experiments in this section was to analyze the capability of the locating tone speakers to aid the blind pedestrians in locating the crossing point from a certain distance of approximately half block away from the intersection. For this analysis, two different types of activating systems were considered – the first type being push button system at intersections Broadway & Fort Street and St. Anne's & Worthington which employ a ticking locating tone, while the other being a non-push button system at intersections Smith St. & York Ave. and Donald St. & York Ave. which relies on the crossing tones to act as locating tone.

Experiment no. 1:

The objective of this experiment is to analyze and understand if there is any significance of the season, high-rise buildings or the activation system apart from the speaker height in locating the crossing point. In the 'Pole Location' section of the questionnaire form, the question which asks about the tones ability to allow location of the crossing point is considered as the response data. As there was more than one response for this observation because of the two directions north-south and east-west, an average of these two observations is considered for ANOVA individually for push button and non-push button type of systems.

Crossing Tones

This section gives details about the two experiments designed for the crossing tones.

Experiment no. 2:

The purpose of this experiment is to analyze the capability of the crossing tone to aid the blind pedestrians in crossing the street at the intersection. The factors considered in this experiment are same as those considered earlier in experiment no. 1 except the factor 'push-button' this testing is for the crossing tone. In the 'Street Crossing' section of the questionnaire form, the question which asks about the tones ability to help cross the street is considered as the response data. As there was more than one response for this observation as well because of the two directions, an average of observations for both the directions is considered for ANOVA as in the previous experiment.

Experiment no. 3:

Crossing tone duration is the pre-set time duration that the ATS tones will be audible after they are activated and the 'Walk' indicator is on. Currently, the city of Winnipeg has set the crossing tone to last for approximately from 5 to a maximum of 7 seconds based on the street width, as a standard at most of the ATS intersections. This experiment is designed to analyze the sufficiency of the tone duration for crossing the street by investigating the effect of the factors seasons – Winter & Summer, speaker heights – 4 ft. & 10 ft. and the intersection complexity (Lanes) on the crossing tone duration. The response considered for this analysis is based on the feedback received for the forth question in the 'Street Crossing' section of the volunteer feedback questionnaire which asks about the tone duration adequacy to cross the street.

Finally when all the data collected from all the three experiments, it is consolidated to analyze it using the statistical software MINITAB® for performing an Analysis of variance (ANOVA). More experiments could have been done on these ATSs but due to limited availability of the funding.

CHAPTER 4

ANALYSIS OF RESULTS

4.1 Overview

The analysis is performed based on the combined data collected during both seasons at different speaker heights and for the four intersections - Broadway + Fort Street, Smith Street + York Avenue, Donald Street + York Avenue and St.Annes and Worthington by 16 visually handicapped volunteers having different levels of visual disability (0% to 10%). The analysis for all the experiments is done by two different methods. First, the ratings for the locating tone ability, the crossing tone ability and crossing tone duration for summer and winter are plotted as shown in figure 4.1. Second, the Analysis of variance (ANOVA) is performed to find the main effects of all factors and the interaction effects between them. These effects have been explained in detail individually in the following sections referring to figures 4.2, 4.3 and 4.4 for the locating tones, the crossing tones and the crossing tone duration respectively.

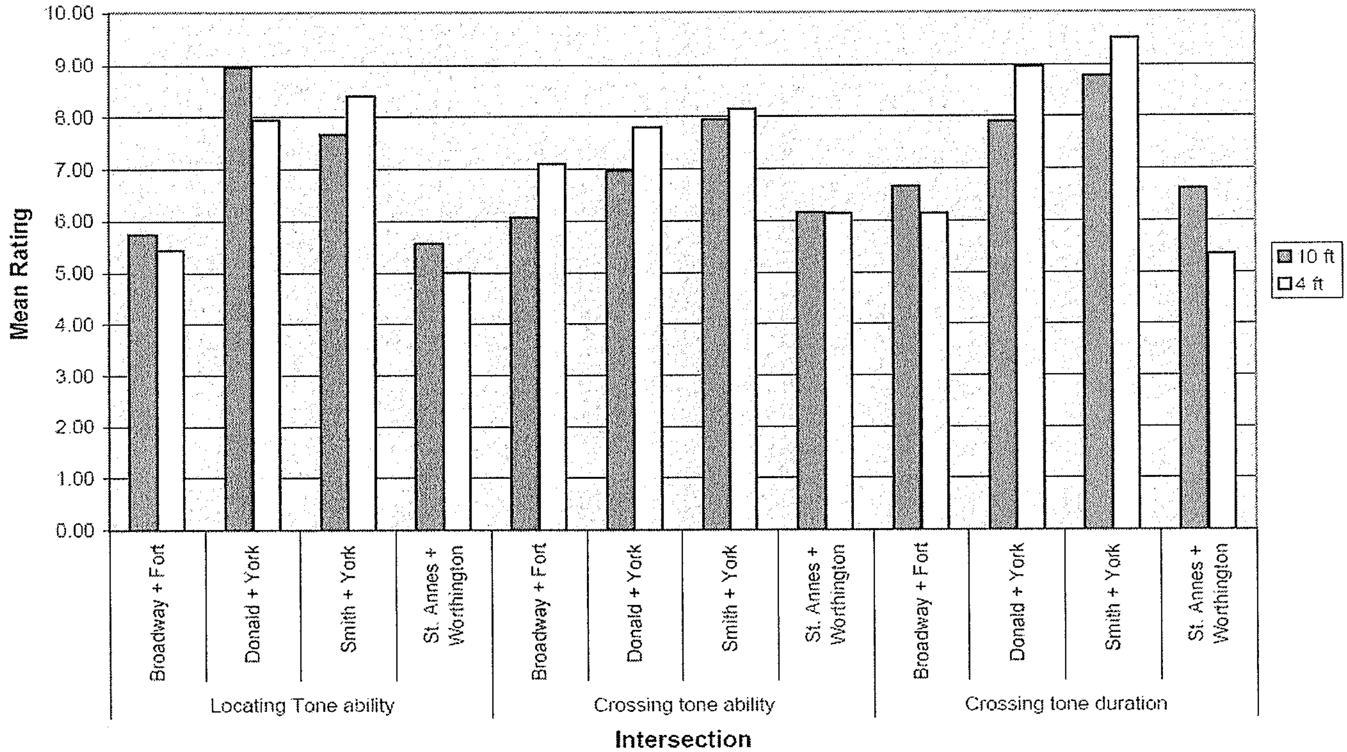


Figure 4.1 a: Analysis of summer experiments

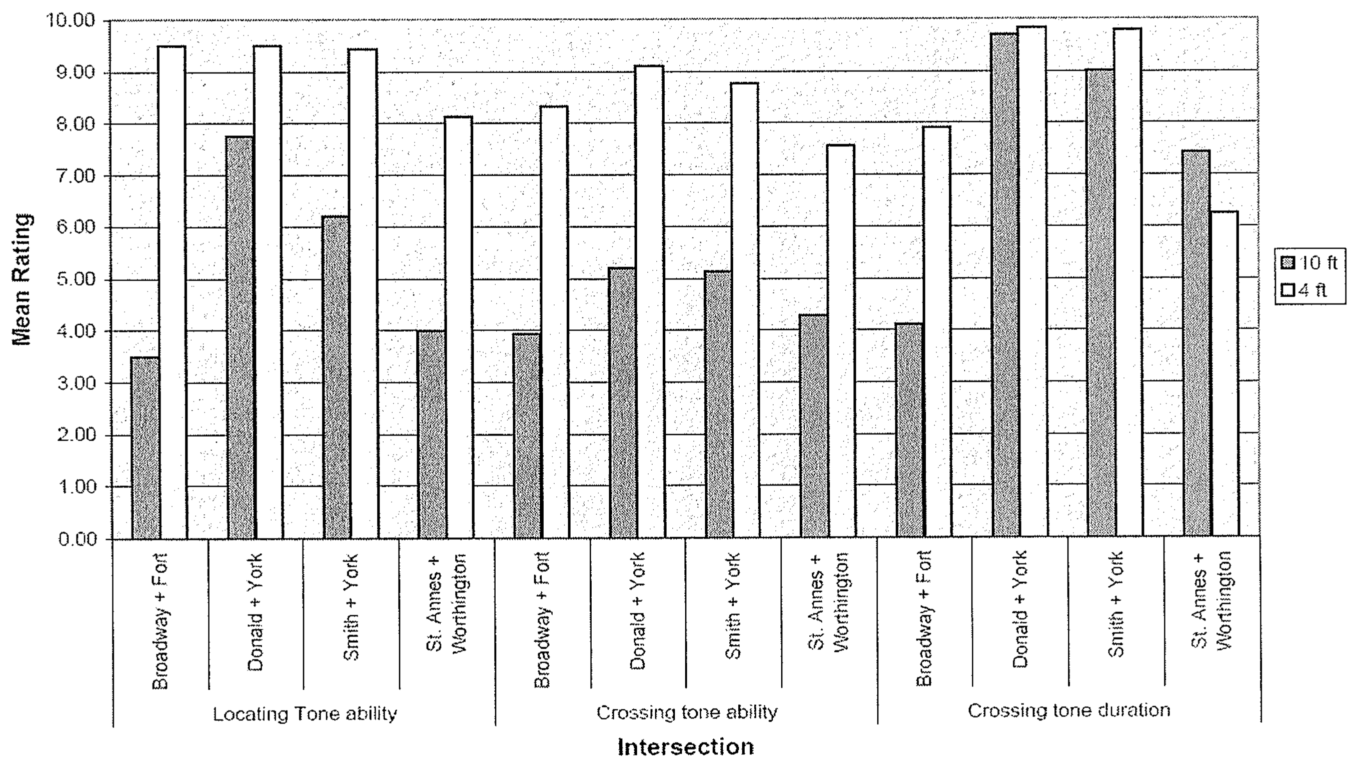


Figure 4.1 b: Analysis of winter experiments

The statistical software MINITAB® has been used for performing ANOVA. As it can be noted from the tabulated results in appendix 4.1, 4.2 & 4.3, ANOVA is run twice for each experiment – first, for a preliminary analysis to identify and remove the unusual observations from the data; second, to find the effect of each factor and the interaction effects between them. The unusual observations were those which had large variations in their values compared to those of other pedestrians. These unusual observations were noticed with one or two subjects in every experiment randomly because of the subjects' varied level of hearing ability as well as visual disability varying between 0% and 10%.

The conclusions are drawn based on the hypothesis tests for each factor and the resultant p-values of their interaction effects as shown in the respective plots in figures 4.2 to 4.4. The p-value is the probability value for rejection of the null hypothesis that the parameter is zero (i.e. not a significant linear factor). For example, a p-value of 0.05 means, that there is 5% chance that the true parameter could be zero. The factors that are significant in each experiment are also highlighted in the ANOVA table for a quick preview.[1]

4.2 Locating Tone

As it can be noted from the histogram for the locating tone ability in figure 4.1, there is not much of difference in the performance for 4 feet height speaker and

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10 feet height speaker during summer. However, in winter it is noted that there is a significant worsening of performance of 10 ft. high speakers, compared to the 4 ft. high speakers due to several reasons that will be discussed in detail in the following paragraphs. Now comparing the locating tone performance in the ANOVA results as tabulated in table 4.1, it can be noted that the factors that are significant are the speaker height and the activation system. Refer to Appendix 4.1 for the original output of the above ANOVA from the statistical analysis software MINITAB®.

Table 4.1: ANOVA results for the Locating tone

Source	**p-value**	**Source**	**p-value**
S	0.480	SH x HR	**0.048**
SH	**0.000**	AS x HR	0.079
AS	**0.000**	S x SH x AS	**0.037**
HR	0.578	S x SH x HR	0.776
S x SH	**0.000**	S x AS x HR	0.789
S x AS	0.787	SH x AS x HR	0.763
S x HR	0.251	S x SH x AS	0.945
SH x AS	**0.005**		

In figure 4.2(a), Seasons and the speaker height interactions plot, it can be noticed that there is no change in the tone performance of the speakers installed at both heights during summer, whereas in winter it shows that the 4 ft. high speakers performed far better (9.2 rating) than the 10 ft. high speakers (5.3 rating). As both curves directly intersect with each other it can be said that there is a significant interaction effect between these two factors. This was also obvious from the volunteer feedback and their comments during the experiments that most of them had a difficulty hearing the ATS tone due to the disturbance caused by the slushing sound of the snow and difficulty in commuting faster between the snow heaps.

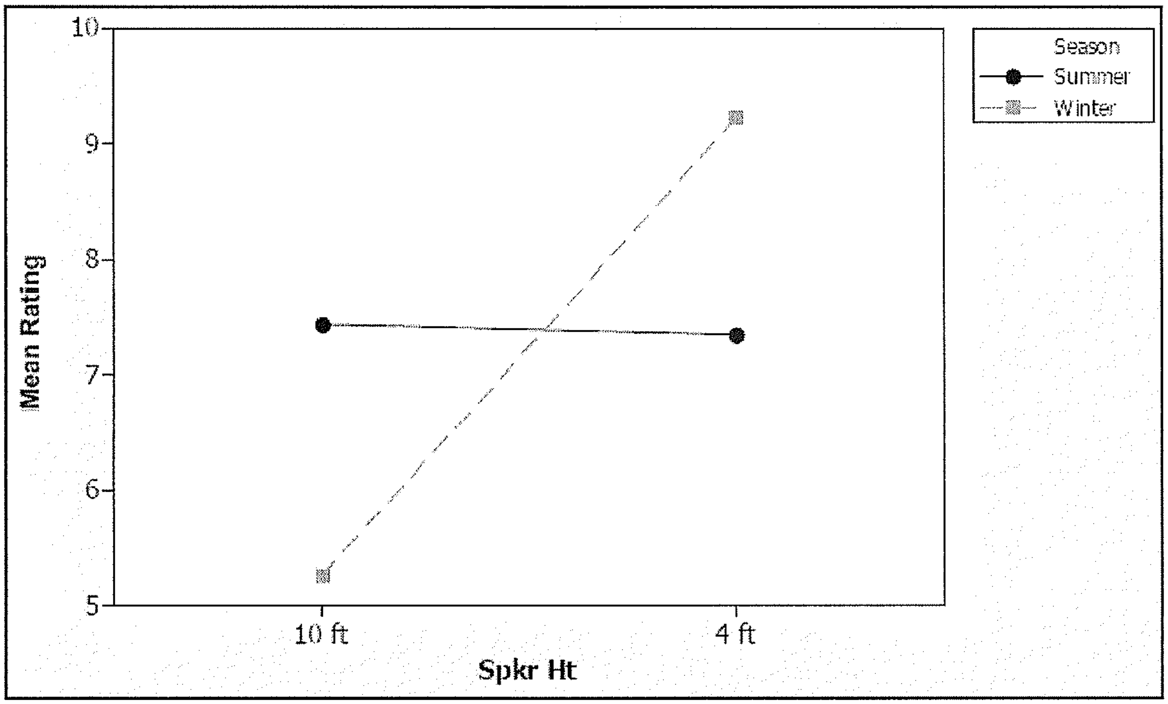


Figure 4.2 a: Interaction plot for Season versus speaker height for the locating tone

Similarly, it can be seen from figure 4.2(b) that the 4 feet high speakers is outperforming the 10 feet and the Non-PB system shows better results compared to the PB type. However the two curves for 4 ft. and 10 ft. are not parallel which means that there is an interaction effect between the speaker height and the activation system. It can be noticed that reducing the speaker height to 4 feet is reducing the difference between the performances of a Non-PB to that of a PB system. Hence it is evident from both figures that lowering the speaker height from 10 feet to 4 feet will greatly improve the performance of the locating tones since the tone from the speakers placed at 10 feet height is allowed to propagate over a larger radius reflecting off several surfaces becoming severely diffused. For the ear to be able to sense the location of an emitting tone, there must be a discernable amount of direct sound from the speaker that reaches the ear before any reflections do. If such a differentiation cannot be made by the brain, a poor sense of the speaker's location results [Barlow, J. M., et. al.]. Moreover it has been learnt from the subject interviews that the Non-PB system is very convenient to use because it is not required to be located and activated.

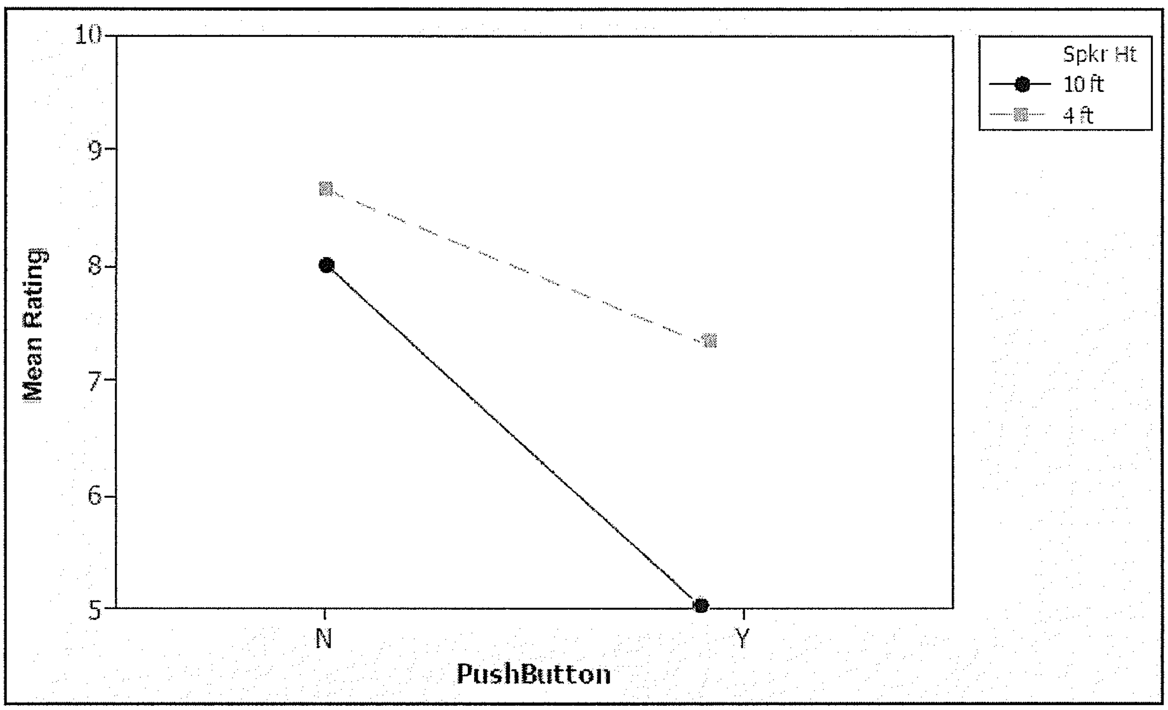


Figure 4.2 b: Interaction plot for Speaker height versus activation system of the locating tone

The interaction plot, as shown in the figure 4.2 (c), illustrates that the Non-PB system performs better than the PB system. Moreover, it can be noticed that the performance of the tones is not affected by the existence of the high-rise buildings with the Non-PB system. However the PB curve indicates that the intersection surrounded by high-rise buildings has better results than the intersection without high-rise buildings. This is apparent from the p-value of the interaction between AS and HR (0.079) which implies that there is only 7.9 % chance for rejecting the null hypothesis for the interaction effect between these two factors. This incongruity is caused due to the intersection of St.Annes + Worthington. Here the system performance should have been better since there were no high-rise buildings but it was poor because of the obstructions in the pedestrian path while locating the crossing point as well as for crossing the street. One of the obstructions was the bus-stop very near to the ATS pole and another one was the telephone as discussed in chapter 5 and figure 5.4.

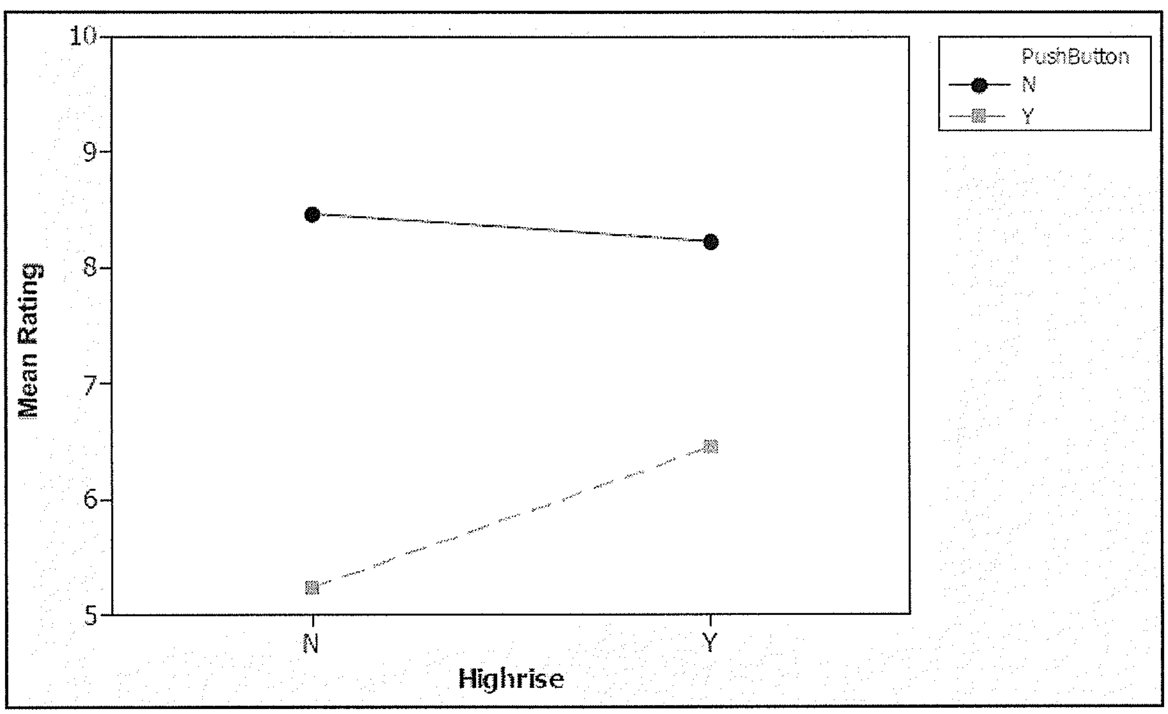


Figure 4.2 c: Interaction plot for activation system versus surroundings of the locating tone

Comparing the two curves in figure 4.2 (d), the 4 feet high speaker again shows better results at the intersection with high-rise buildings. However, for 10 feet high speaker the ATS performance worsens for the intersection with high-rise buildings. This could be attributed to the reduction in echoing effects at Smith Street and York when the speakers are installed at 4 feet height.

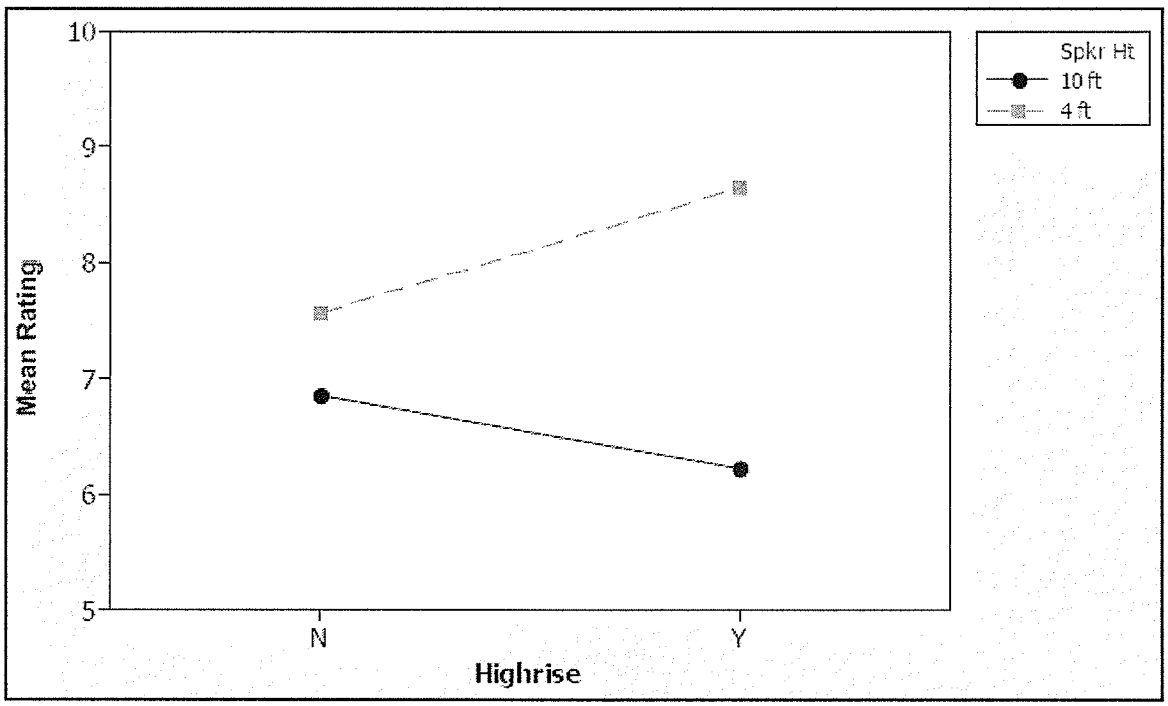


Figure 4.2 d: Interaction plot for speaker height versus surroundings of the locating tone

4.3 Crossing Tone

The results of the crossing tone experiments also show similar results to the results of locating tone ability experiments. Referring to figure 4.1 there is no significant difference in the tone ability for 4 feet height speaker and 10 feet height speaker during summer for all the intersections, the ratings for both heights are very near to each other. However, in winter there is a considerable amount of improvement in the ability of 4 ft. high speakers, compared to the 10 ft. high speakers. The possible reasons are already explained in the section 4.2.

Based on the factors discussed in section 3.3, an analysis of variance is performed for crossing tones. The ANOVA result summarized in table 4.2 and the significant factors / interactions are highlighted. Refer to Appendix 4.2 for the full output of the ANOVA results from the statistical analysis software MINITAB®.

Table 4.2 : ANOVA results for crossing tone

Source	**p-value**	**Source**	**p-value**
S	**0.000**	S x HR	0.143
SH	**0.000**	SH x HR	0.354
HR	0.364	S x SH x HR	0.388
S x SH	**0.000**		

As it can be noted from table 4.2, the factors Season and Speaker height are highly significant. As both the curves intersect each other as illustrated in figure 4.3(a), interaction between these two factors also is very significant. This implies that there is no difference in the crossing tone ability during summer for both heights. But, in winter there is a significant effect in the ability of 4 ft. high speakers which has improved compared to the 10 ft. high speakers. One of the reasons as already explained in the previous section could be due to the slushing sound of snow which distracts the pedestrians and dominates over the ATS tones. Secondly, the tone from '10 feet' high speakers is allowed to diffuse more severely resulting in a poor differentiation between direct and reflected sound than that of a slightly lower speaker of 4 feet high.

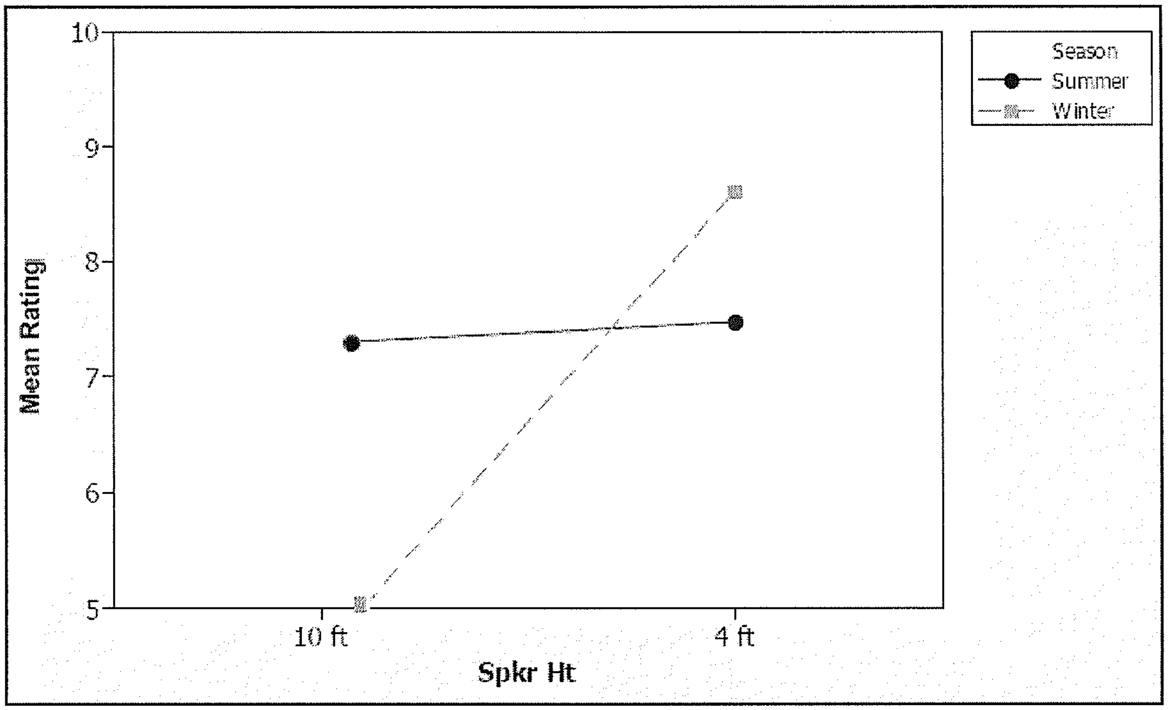


Figure 4.3 a: Interaction plot for Season versus speaker height of the crossing tone

The curves in figure 4.3(b) show that there is no significant interaction effect between the Season and the Existence of high rise buildings. This means that the difference between the tones audibility at intersections with HR and Non-HR remains the same for 4 feet and 10 feet high speakers. Or simply, change in the surroundings doesn't affect the performance of tones in both seasons. However it can be seen that the summer curve outperforms the winter curve at intersections with or without high-rise buildings.

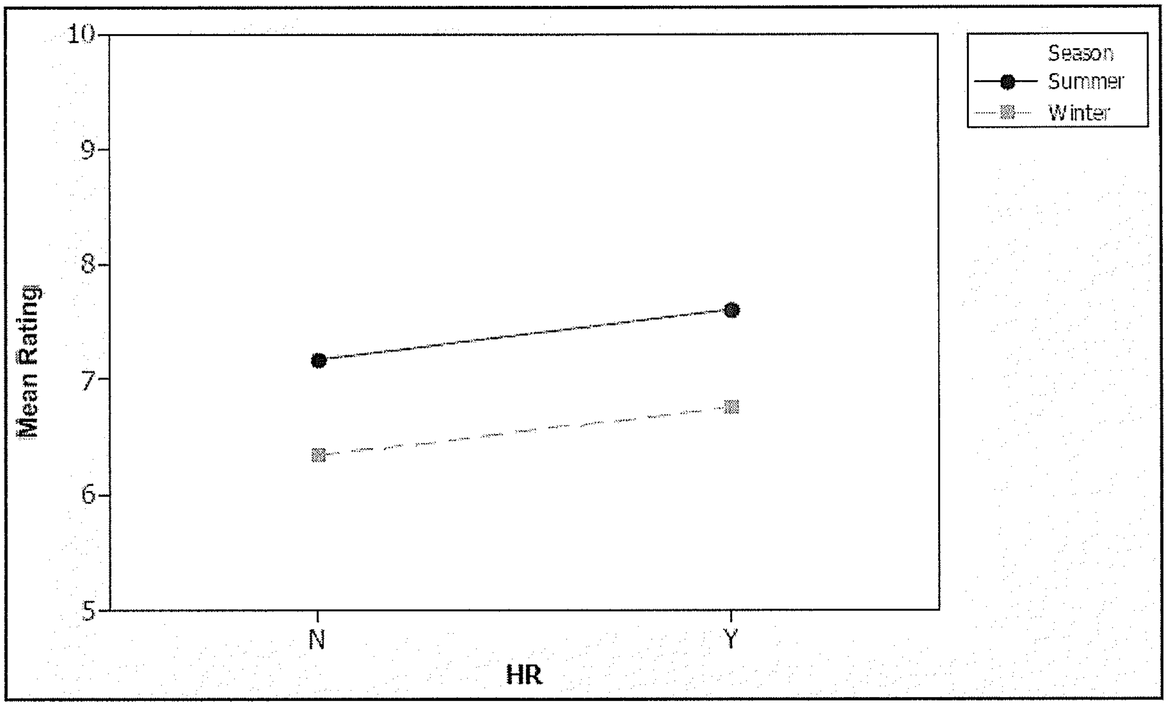


Figure 4.3 b: Interaction plot for Season versus surroundings of the crossing tone

Figure 4.3(c) shows very similar effects as in the previous figure that there is no significant interaction effect between the Speaker height and the existence of high rise buildings. This means that the difference between the tones audibility at intersections with HR and Non-HR remains the same for 4 feet and 10 feet high speakers. However speaker height of 4' outperforms 10' at intersections with or without high-rise buildings.

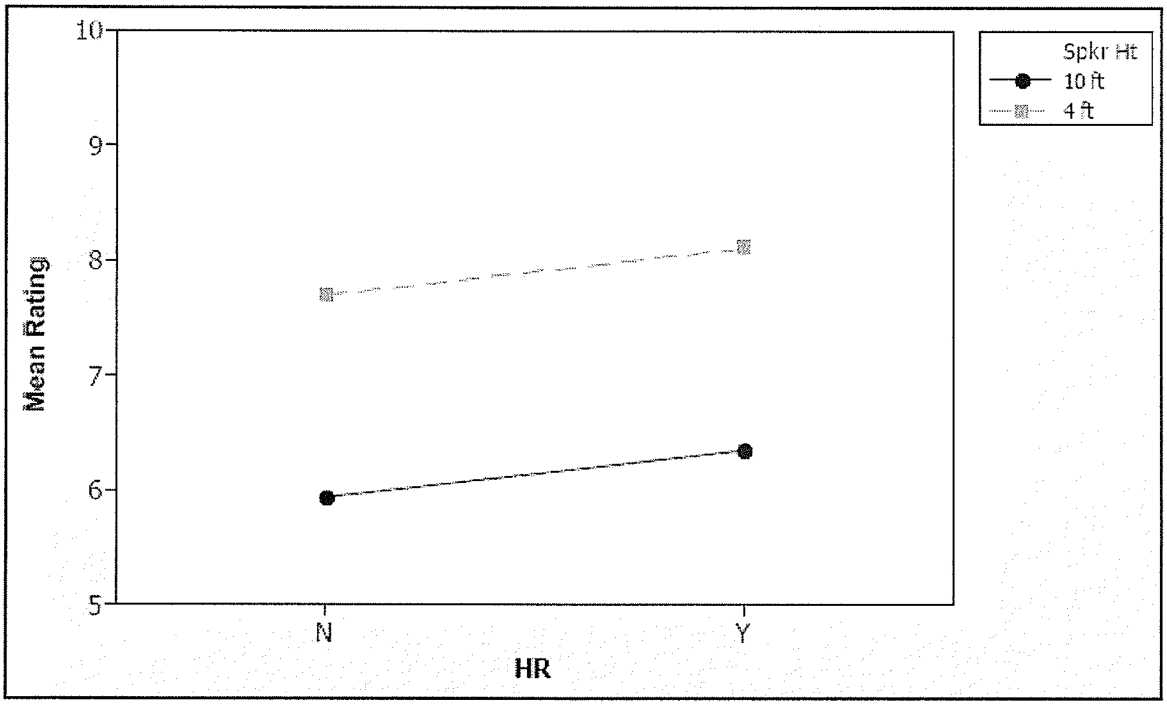


Figure 4.3 c: Interaction plot for Speaker height versus surroundings of the crossing tone

4.4 Crossing tone duration

Crossing tone duration is the pre-set time duration that the ATS tones will be audible after they are activated and the 'Walk' indicator is on. Currently, the city of Winnipeg has set the crossing tone to last for 7 seconds as a standard at most of the ATS intersections. The analysis of the Crossing tone duration is somewhat different compared to the locating tone and the crossing tone. As this experiment is performed to test the crossing tone duration, the factors AS and HR are not relevant and hence deleted from the analysis. However a new factor Lanes (L) has been considered since the number of lanes or street width will affect the pedestrian walking speed as suggested by Laplante, J. N. and Kaeser, T. P. (2004).

The histogram for the crossing tone duration in figure 4.1 did not give the complete idea of the crossing tone duration. However, the results of the ANOVA performed for the crossing tone duration were unambiguous and are summarized in table 4.3. The factors that are significant are highlighted for a quick preview. Refer to Appendix 4.3 for the full output of the ANOVA results for the crossing tone duration.

Table 4.3: Analysis of Variance for Crossing tone duration

Source	**p-value**	**Source**	**p-value**
S	**0.003**	S x L	**0.000**
SH	0.352	SH x L	**0.046**
L	**0.000**	S x SH x L	**0.016**
S x SH	**0.010**		

Referring to table 4.3, the null hypothesis for the effect of the season can be rejected for a significance level $\alpha \geq 0.003$ which means that there is a significant effect of the season. However the factor speaker height doesn't have any significant effect as the p-value is 0.352. Logically, it can be assumed that, during winter there may be lots of snow heaps around the crossing points at the intersections or even on the streets which may result in the duration of the tones to be insufficient to cross the street. However, it turns out to be false as per figure 4.4 (a) where the results of winter were almost in same line as those in summer. Infact the performance rating in winter can be seen as slightly better than that in summer. After a careful review of the videos that were taken during experiments and comparing the videos of summer versus winter it was discovered that during summer many subjects were either deviating from the path or unable to recognize the path quickly. Whereas in winter none of the subjects seemed to deviate from the cross walk; they were able to cross the streets quickly. After a thoughtful investigation it was noted that during winter when the experiments were done it was already dark. As such, the partially blind subjects were able to recognize correct path with the help of the street lights, flashing indicators and the moving vehicular lights without deviating. Whereas, in summer the experiments were done at the same time but there was plenty of sunlight. As such there was no other guidance except the tones and the vehicular sounds. Moreover, the snow paths created in winter on the pavements as well as on the streets also help a lot to both partially blind and fully blind subjects.

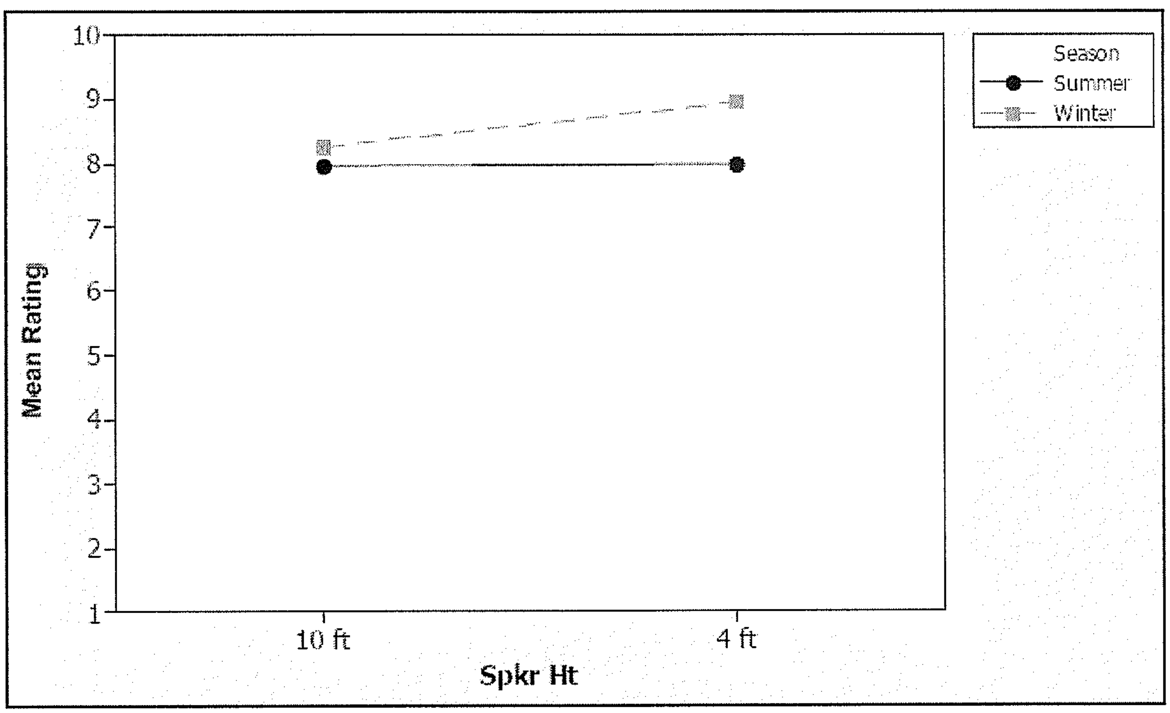


Figure 4.4 a: Interaction plot for Season versus speaker height of the crossing tone duration

As discussed earlier figure 4.4 (b) also shows similar performance ratings. The effect of season, lanes and interaction between them is very significant. It can be noted that in both seasons as the number of lanes is increased the performance rating decreased. It is obvious from the simple fact that as the number of lanes increased the travel distance also increased, but the duration of the tones wasn't set in proportion to this increase; as mentioned earlier it set to a maximum of 7 seconds. However, this was not true when comparing 2 lanes to 4 lanes. It turns out that these two intersections do not have medians which made it easier to cross the street on time compared to the other two intersections of Broadway + Fort and St.Annes + Worthington.

Now, when the interaction of season with lanes is taken into consideration, it follows the same trend of winter better than summer as in the figure 4.4 (a), except for the intersection of Broadway and Fort which has eight lanes with a median. Unlike all other intersections, the intersection of Broadway and Fort is very confusing not only for the fully blind but also for the partially blind subjects because of the median. At this intersection, the pedestrians had to first search for the locating pole between the snow heaps, activate the ATS and wait at the median for another chance to cross the second half. This problem was more severe in winter and the performance rating was marked as low as 2 for the intersection of Broadway and Fort Street.

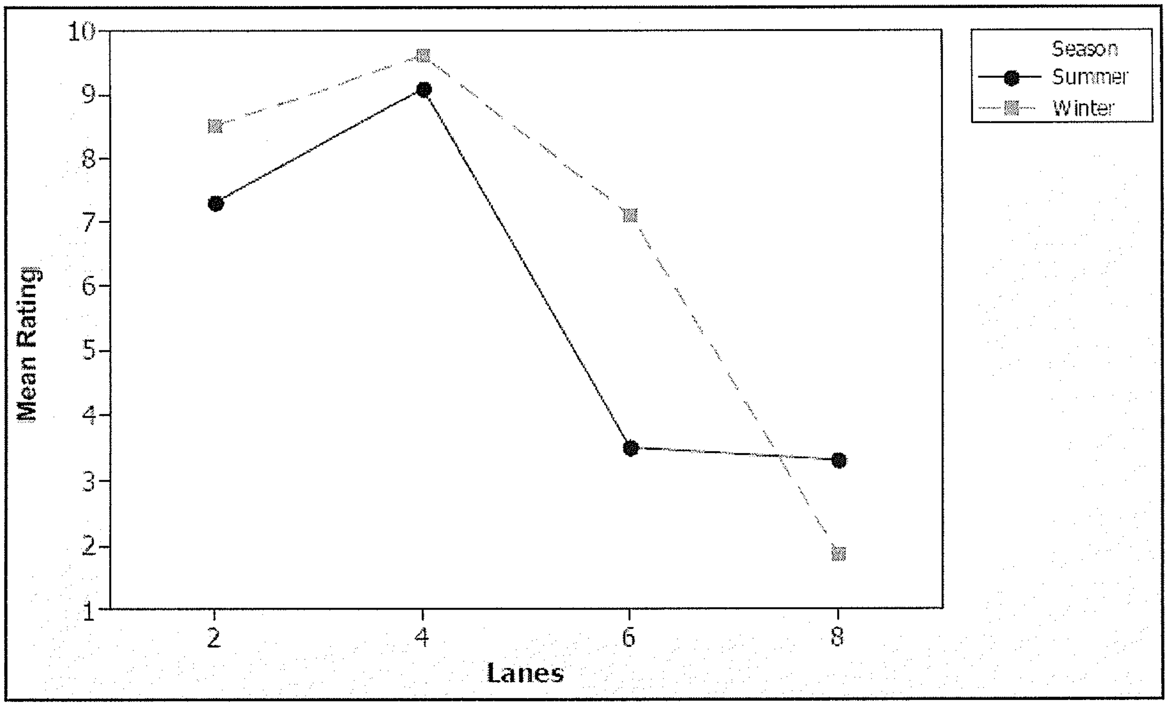


Figure 4.4 b: Interaction plot for Season versus no. of lanes of the crossing tone duration

Referring to figure 4.4 (c) the null hypotheses for the effect of number of lanes can be rejected for a significance level $\alpha \geq 0.000$. Consequently, this means that there is a significant effect on the crossing tone duration due to the change in the number of lanes at the intersections. As it can be seen in the figure 4.4 (c), with the increase in the number of lanes from 2 to 8, the tone duration became more and more insufficient except for the street with 4 lanes. Logically, one would assume that as the size and complexity of the intersection increases, the performance of the crossing tone duration would decrease, as the sound would be required to travel over a farther distance and so is the pedestrian using the signal. Looking at the ANOVA results in table 4.3, all the data agrees with this trend except for the street with four lanes which are at Smith + York and Donald + York. It turns out that these two intersections do not have medians which made it easier to cross the street on time compared to the other two intersections of Broadway + Fort and St.Annes + Worthington.

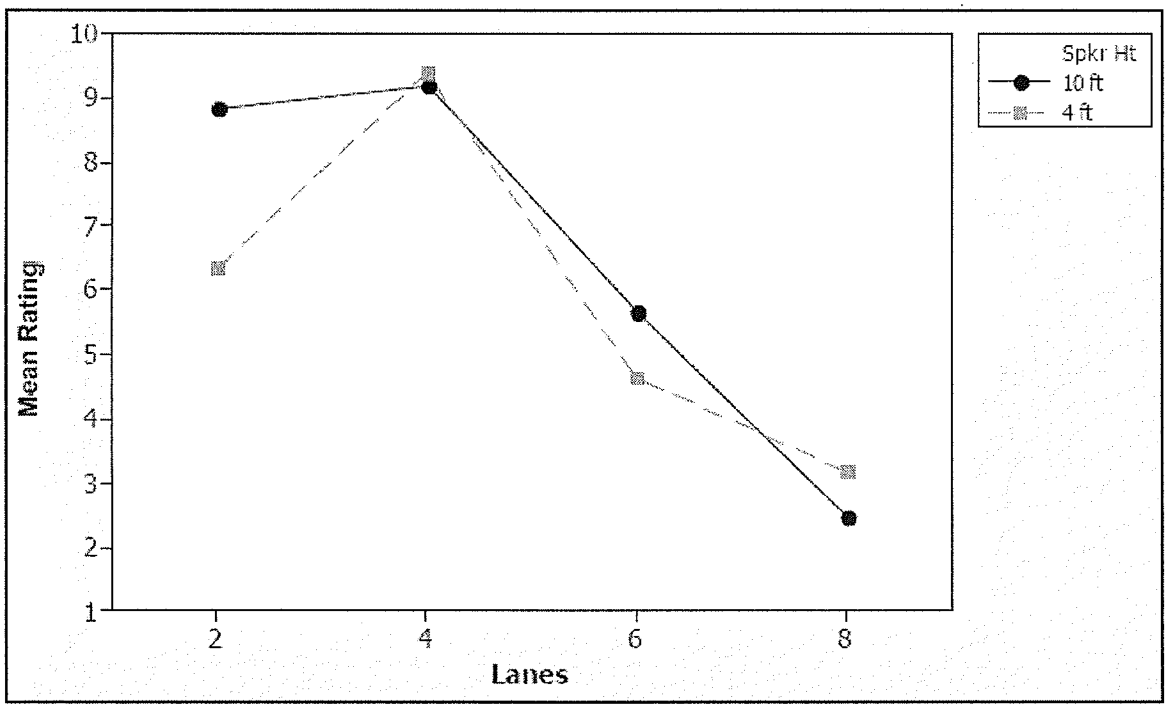


Figure 4.4 c: Interaction plot for speaker height versus no. of lanes of the tone duration

Although crossing tone duration performance seems to vary with intersection size and complexity, the amount of improvement introduced by lowering the speaker to 4 feet seems to be fairly constant for each intersection. As a result, it appears as though lowering the speaker height to 4 feet does little to counteract the effect of intersection size and complexity. An important remark related to the above analysis is that the crossing tones at St. Anne's & Worthington and Broadway & Fort only last for 7 seconds while the crossing tones at the other two intersections stay on for the entire duration of the crosswalk light. This surely had an impact on the ratings given to Broadway & Fort's N/S crossing and St. Anne's and Worthington's E/W crossing, as they both require far longer than 7 seconds to traverse. Unfortunately, this introduces some uncertainty into the above conclusions about the effects of intersection size and complexity.

4.5 Conclusions

The testing undertaken at the four selected intersections provided a lot of insight into how much impact the speaker height and other factors had on the overall performance of the audible pedestrian signal system. From the tests performed on the locating tones, it was clear that lowering the speaker height from 10 feet to 4 feet provided a marked improvement in the overall performance of the locator tones for all of the tested intersections. When looking at the effect of the other factors, the only factor that appeared to have any major influence on the results was the season. Moreover as it has been noted from section 4.2 that reducing the speaker height to 4 feet is reducing the difference between the performances of a non-PB to that is a PB system. When observing the results obtained for crossing tone performance, it can be concluded that all tested intersections benefited from the lowering of the speakers to 4', although the margin of improvement was minimal in all cases. The other factors that had major influence on the results were season, intersection size and complexity. However, when considering the effect of lowering the speaker height to 4', very little difference in improvement was evident between the large and small intersections. As a result, the lower 4' setting did little to eliminate the effect of intersection size and complexity on the performance of the crossing tones.

In the experiments conducted for both the locating tone and the crossing tone, it was noted that the performance rating for the observation in summer were better than those in winter. As far as the locating tone duration was concerned, it was noted vice versa. Moreover, the ANOVA results showed that there was a significant effect of the season on the tone duration. In view of the above, a further study on crossing tone duration in different seasons similar to that done by LaPlante J.N., and Kaeser T.P., 2004 can be recommended by taking into consideration other factors such as number of lanes, the existence of median and intersection complexity. Secondly, the assumption that "as the number of lanes increases, the performance of the crossing tone duration would decrease" doesn't hold good for the street with four lanes which are at Smith + York and Donald + York. These two intersections do not have medians which made it easier to cross the street on time compared to the other two intersections of Broadway + Fort and St.Annes + Worthington.

Apart from the issues identified from the feedback of the blind subjects, several unidentified issues also were brought to light by a thorough clip by clip visual analysis of the recorded videos that were taken during the experiments and the test co-coordinator's observations at the surroundings. These issues and their potential solutions have been generalized and presented in detail in the next chapter along with the final conclusions.

CHAPTER 5

OTHER IDENTIFIED ISSUES AND POTENTIAL SOLUTIONS

Apart from the general questionnaire that was available to collect the data, there were provisions in the same form to get additional comments or ideas that the volunteers would like to share. Through these comments a few issues although simple but demanding such as installation, maintenance and other miscellaneous issues were identifiable. A list of these issues is given below along with their suggested potential solutions.

5.1 Localization of Blind Spots

The power behind a blind pedestrian's ability to cross a traffic intersection using an ATS system lies in his brain's capability to sense the source and location of the audible signal. Normally any ATS will have a speaker installed on either sides of a street at the curb that generates the same tone simultaneously. At a point in the middle of the street where the intensity and phase of the sound received by both ears is the same, the brain cannot sense whether the sound is coming from directly in front or directly behind. These are called as Localization of blind spots. Refer to figure 5.1 which explains this situation. To counteract the effect of Localization of blind spots, it is suggested that alternating tones be introduced, possibly using two different tones at the two speakers.

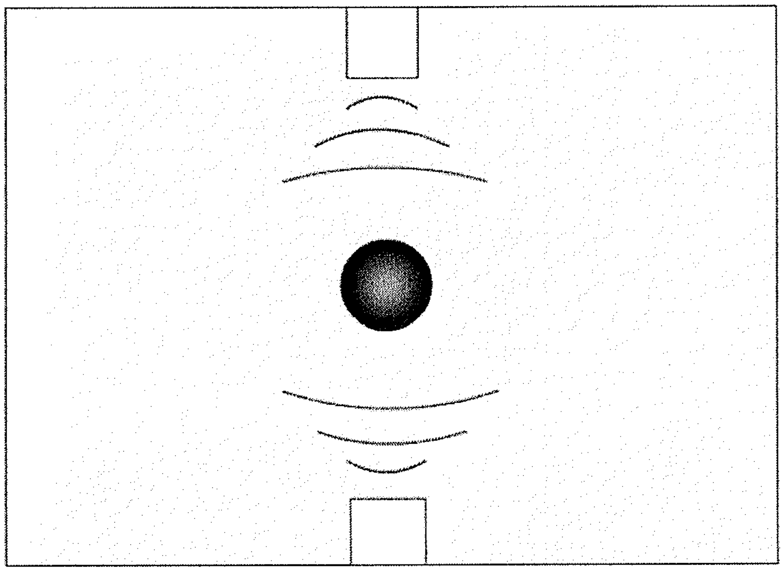


Figure 5.1: Localization of blind spot[Thesis 2005 – Jordan Lanoway]

Several studies have been done on this topic including work by Ono et al. (1999), Tauchie et al. (1998) and Laroche et al. (2000). Conclusive evidence gathered by these teams has shown that the use of alternating different tones can totally eliminate the existence of blind spots, enabling the pedestrian to stay focused on the crossing tone at all times.

5.2 Near - Far Effects

As mentioned before, a pedestrian's sense of distance is partly determined by the intensity of each emitted tone from a given speaker. Therefore, the speaker nearest to the pedestrian usually sounds the loudest, while the speaker farthest away, usually sounds the quietest. However, with the use of the auto-volume sensor, it is quite possible that at any point in time, the farthest speaker could suddenly become the loudest. That's because the auto-volume sensor located at a certain speaker senses its ambient sound and controls the volume of that particular speaker accordingly. Due to this the pedestrian looses his/her sense of speaker location. This problem is amplified in a dynamic environment such as downtown rush hour, when each speaker's volume is constantly changing, making it more difficult for the pedestrian to locate the speaker pole. This effect is known as Near - Far effect.

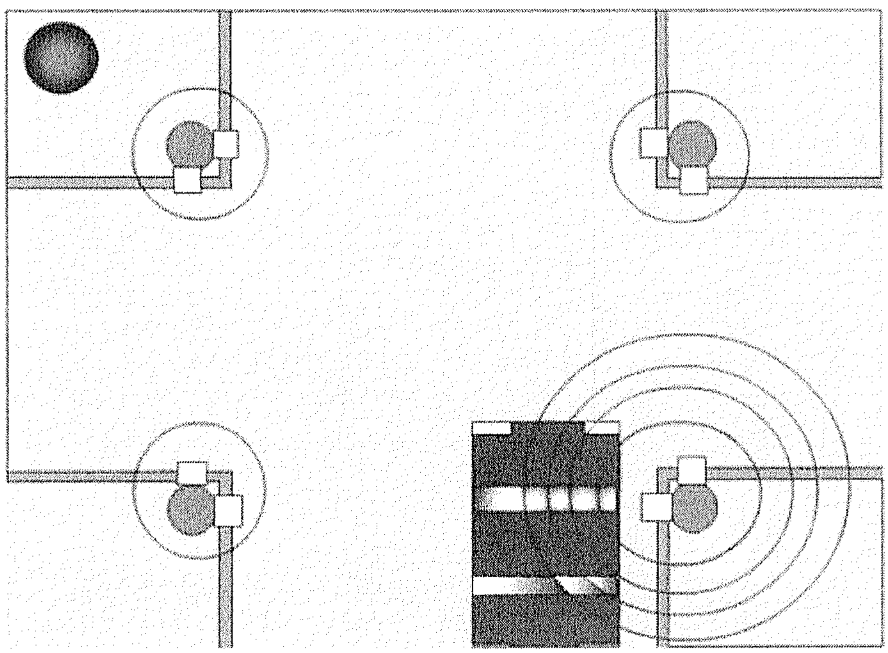


Figure 5.2: Near and Far Effects [Thesis 2005 – Jordan Lanoway]

To counteract the Near - Far effect, it is suggested that the auto-volume sensors at the four corners of an intersection be coordinated so that one does not have the ability to overpower the others. Although this suggestion is logical, it might not be immediately feasible in Winnipeg, as most intersections lack the necessary wiring between corners required to make the idea work. Further research will be needed to prove the effectiveness of such a system.

5.3 Installation & Maintenance

The City of Winnipeg has installed approximately 200 systems most of which were installed in the last 5 years. Apart from the four intersections that were tested, a variety of other kinds of issues existed at a few other intersection in the city. These issues may not be directly related to ATS systems but have an important role to play in crossing the streets safely, especially for the visually impaired pedestrians. To mention a few these are the improper installation of the fire hydrant, telephone pole, etc. as illustrated in figures 5.3 through 5.8.

Figure 5.3: Fire hydrant in the path of a crosswalk [Thesis 2005 – Jordan Lanoway]

For example, figure 5.3 shows a fire hydrant installed in the path of the crosswalk at the South East corner of Broadway and Fort intersection. Figure 5.4 shows a telephone pole installed directly in the path of the crosswalk in the path causing a lot of hindrance to the pedestrians crossing the streets, especially the visually impaired persons who might not even guess of an existence of such an obstruction in their path. When the tests were performed at this intersection, several volunteers mistook the telephone pole for the crosswalk pole and attempted to find the activation button attached to it without ever realizing that the real pole was a few feet right ahead of it.

Figure 5.4: Telephone pole in the path of a crosswalk on St. Annes

Other examples include the South-west corner of St. Anne's & Worthington and the South-west corner of Broadway & Fort as illustrated in figures 5.5 and 5.6

respectively. The Broadway & Fort corner is an example of what a proper system configuration looks like: one pole containing the speakers and push buttons for both the N/S and E/W directions, emitting one locating tone from one location (Figure 5.6). The St. Anne's & Worthington corner, on the other hand, is an example of a poorly installed system. As two poles originally existed at this corner before the audible system was installed, the simple solution was to install individual systems on each pole (Figure 5.5). However, this has resulted in a corner with two identical locating tones emitted from two different locations. During the tests, several of the volunteers could not distinguish between the two locating tones, causing some to assume that there was only one pole. To counteract this problems it is suggested that pole location and the push button orientation should be standardized and maintained at the same level at all intersections in the city.

Figure 5.5: ATS Speaker on different poles at St.Annes & Worthington[Thesis 2005 – Jordan Lanoway]

Figure 5.6: ATS Speaker on the same pole at Broadway & Fort [Thesis 2005 – Jordan Lanoway]

Figure 5.7 shows an example of the Push button pole on the median on Broadway intersecting at Fort Street. Broadway has four lanes in each direction and Fort Street is a two lane one-way street going north bound. This pole has a push button but there are no speakers. A blind pedestrian who wants to cross Broadway will only assume that there is no push button and may proceed with crossing the second half of the street assuming that the crossing tone is good for crossing the complete street.

Figure 5.7: Median push button on Broadway & Fort Street.

Another situation experienced during the winter experiments is the intersection at the North-west corner of Broadway & Fort which is a good example of poor snow removal as illustrated in figure 5.8. It is literally inaccessible to any pedestrian with or without vision as the push-button pole is about 6 feet away from the crosswalk and its path is buried in snow.

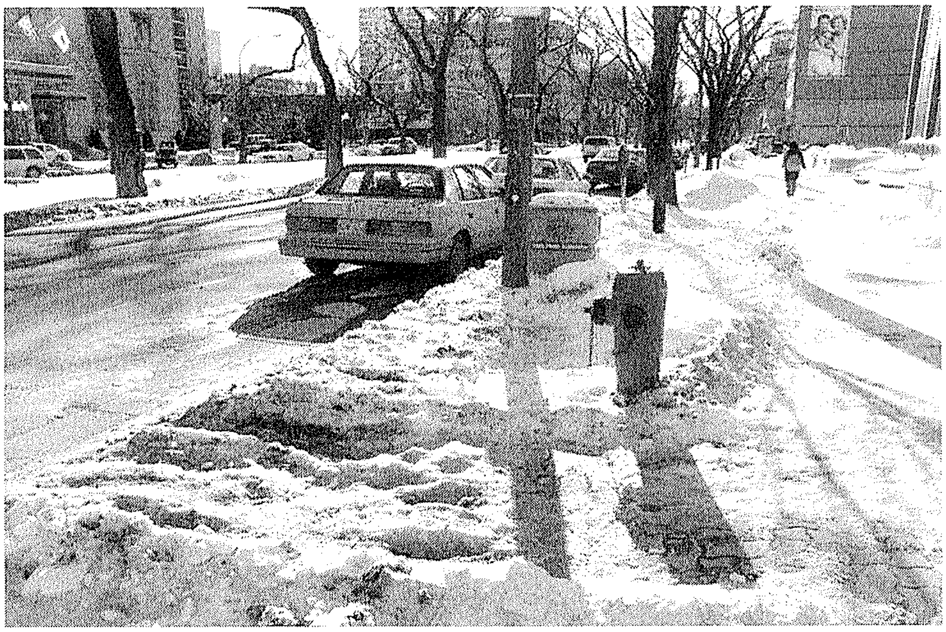


Figure 5.8: Crosswalk obstruction due to snow. [Thesis 2005 – Jordan Lanoway]

5.4 Summary

Reviewing through the complete chapter it can be concluded that most of the issues discussed above, especially the seasonally issues add to the advantages of a non-push button type system as there is no need for the system to be accessed prior to crossing the streets. These systems would make even more convenient for the blind pedestrians who carry a guide dog or a cane. Moreover for a city like Winnipeg where the winters are as severe as -40 degrees C, one needs to wear winter clothing for almost 6-8 months. In such clothing conditions it may be very difficult for the visually impaired pedestrians to locate the push button.

The blind spot problem was similar to one of the experiments conducted by Tauchi et al. (1998) whose results showed that the alternating pattern using different sounds achieved better results and that subjects were always able to identify the sound source along the entire crosswalk using this pattern. The near – far effect also is another pedestrian orientation problem which needs coordination between the auto-volume sensors at the four corners of an intersection. However further research will be needed to prove the effectiveness of such a system.

The installation issues such as the fire hydrant and the hydro pole obstruction are also the serious issues. Such installations should be well coordinated with the respective departments prior to their installation. These issues may not look serious but in winter they can be hazardous.

CHAPTER 6

SPEAKER DESIGN AND MANUFACTURING

6.1 Introduction

The objective of this research was to assess the effectiveness of ATS devices, identify the root cause of all the barriers discussed in Chapter 1 through an intensive research and a thorough analysis of designated experiments. Another objective was to design a speaker for the ATS that can be mounted more streamlined on the pole or inside the pole whose sound level is pre-set to the level where it can be clearly heard by a person with visual impairment and will not disturb the people living close by in the community. As lowering the speaker height is the key aspects of the study, it was also necessary that the speaker construction should be vandal proof. Furthermore, as the new speaker had to be installed on the existing ATS pole it was also necessary that the dimensions of the new design must be slim & compact, and should match those of the pole unlike the existing ATS speaker that has a cube shape box protruding out more than 10 cms and can easily be vandalized.

The ATS speaker that is currently used by the City of Winnipeg's traffic department is illustrated in figure 6.1. This is a conventional diaphragm type speaker enclosed in a vented box and has a vibrating diaphragm inside that generates sound waves by the fluctuations in air pressure. These kinds of speakers are normally used for in-house applications such as music systems, TV sets, calling bell, etc. It may not be appropriate to make a direct comparison of these kinds of speakers with the proposed exponential loudspeaker horn as each of these has their own advantages and disadvantages depending on the application that they have been designed for. However, an attempt has been made to change the existing speakers for the reason that the ATS tones generated by the current speakers are overpowered by the traffic noise in heavy traffic conditions. A speaker using a horn design has the ability to play louder with lower levels of distortion than a conventional speaker using direct radiators.

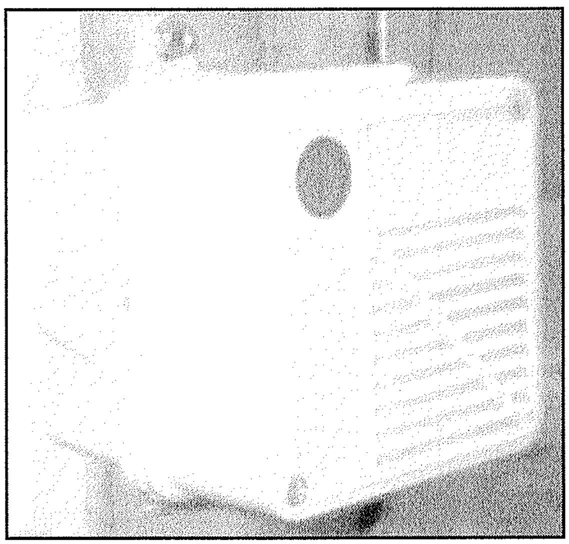


Figure 6.1: The ATS speaker currently used in the city of Winnipeg

The design of the proposed ATS speaker is based on a simple loudspeaker horn. This section emphasizes on the fact that the sound from a speaker having a loudspeaker horn system will be more dynamic and efficient than that from closed/vented boxes. That is because the acoustic horn transforms high pressure at the throat to a low pressure distributed over the large mouth of the horn, or simply transforming high-energy/small movement to low-energy/large movement of air (figure 6.2 & 6.3).

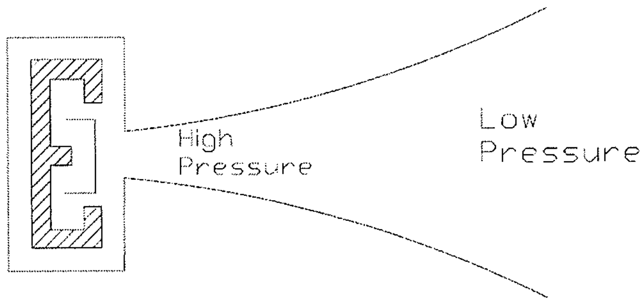


Figure 6.2: The exponential horn principle

Figure 6.3: The exponential horn used in the proposed ATS speaker

The speaker horn forms a funnel starting at the *throat* which is closest to the driver and ending at the *mouth*. It can be of different contours such as the conical, exponential and hyperbolic contours of which the conical is the easiest one to calculate and assembled into a box, but it is also the least efficient. Conical contours are never employed for bass horns because of the poor response and the impossibly long horns that result. The exponential is the most commonly used, and is easy to calculate. The hyperbolic contour is actually a variation of the exponential, and is an efficient type but it is somewhat longer than the exponential. Therefore an exponential type of horn whose efficiency reaches as high as 40-50% has been selected to design this speaker. As some basic knowledge about the physics of an exponential horn would help better understand the proposed speaker design, the basics of Horn Physics is discussed below in brief.

As similar to a conventional loud speaker, when an ordinary solid diaphragm speaker is coupled with a horn, the speaker is able to play louder with the same amount of input power as compared to a conventional speaker. This is because the sound generated by the motion of the solid diaphragm is transferred to the horn before letting is out to the fluid air. Due to its increasing cross-sectional area, the horn increases the pressure of the sound wave and accelerates the sound through the thinner portion of the horn. This reduces diaphragm motion and lowers distortion allowing more acoustic power per unit area, unlike a conventional speaker using direct radiators.

King M.J. 2002, studied various horn geometries and concluded that an exponential horn is more efficient compared to alternate horn geometries including linear and conical. The basic theory of an exponential horn as explained by King is discussed as follows. Figure 6.4 illustrates the basic geometry required to define an exponential horn.

In figure 6.4, if the area at the throat is S_0, the area at the mouth is S_L, and the length L defines the flare constant m of the exponential horn, then:

The flare constant, $$m = \frac{ln\left(\frac{S_L}{S_0}\right)}{L}$$

The lower cut-off frequency, $f_c = \dfrac{mc}{4\pi}$ where c is the velocity of sound in air

And the area at the mouth, $$S_L = \frac{\left(\frac{c}{2f_c}\right)^2}{\pi}$$

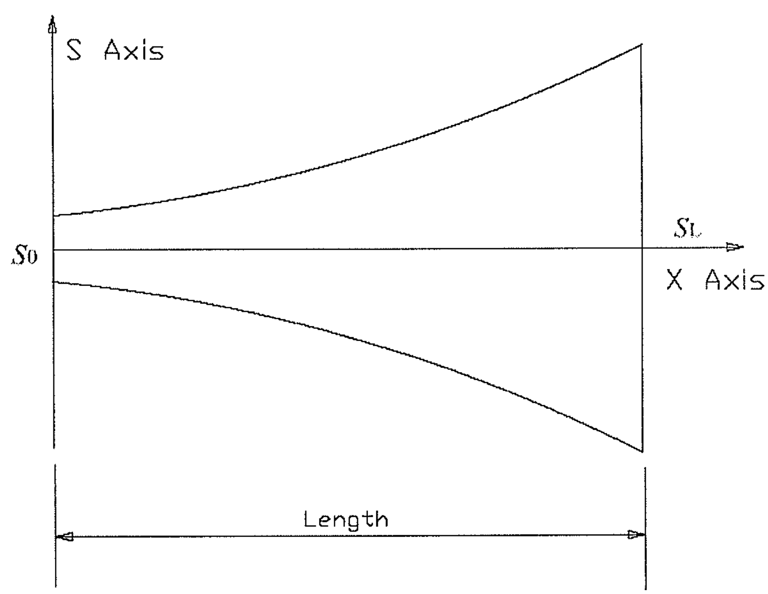


Figure 6.4: Basic geometry of an exponential horn [*King, M.J., 2002*]

Based on the above equations, King plotted the acoustic impedance at the throat and the ratio of the volume velocities for the horn geometries. He noted that the acoustic impedance at the throat of an exponential horn becomes purely resistive above the lower cut-off frequency and has an easily predictable magnitude. As the horn's throat becomes smaller the acoustic resistance rises.

Finally, King concluded that when the frequency is above the lower cut-off frequency of an exponential horn, the volume velocity at the mouth is greater than the applied volume velocity at the throat. Since the throat area decreases with an increase in the horn length, the ratio of the volume velocities grows. The sound pressure level produced by the horn mouth is dependent on the volume velocity of the mouth. Hence as the exponential horn's length increases the overall efficiency of the horn increases.

6.2 Design of Proposed Speaker Box

The conceptual design for the proposed ATS speaker box has been initiated by Dr. D. Strong at the University of Manitoba. As a continuation of this research on the ATS performance, Dr. Strong's conceptual design has been further studied and a detailed design is developed. Based on this design, eight prototypes of the ATS speaker are manufactured that consisted of a rectangular shaped metal enclosure. It has an exponential horn coupled with a rectangular shaped sound duct having an exponentially increasing area of cross-section (figure 6.5). The horn is fixed at the top portion of an angular bracket on the base plate.

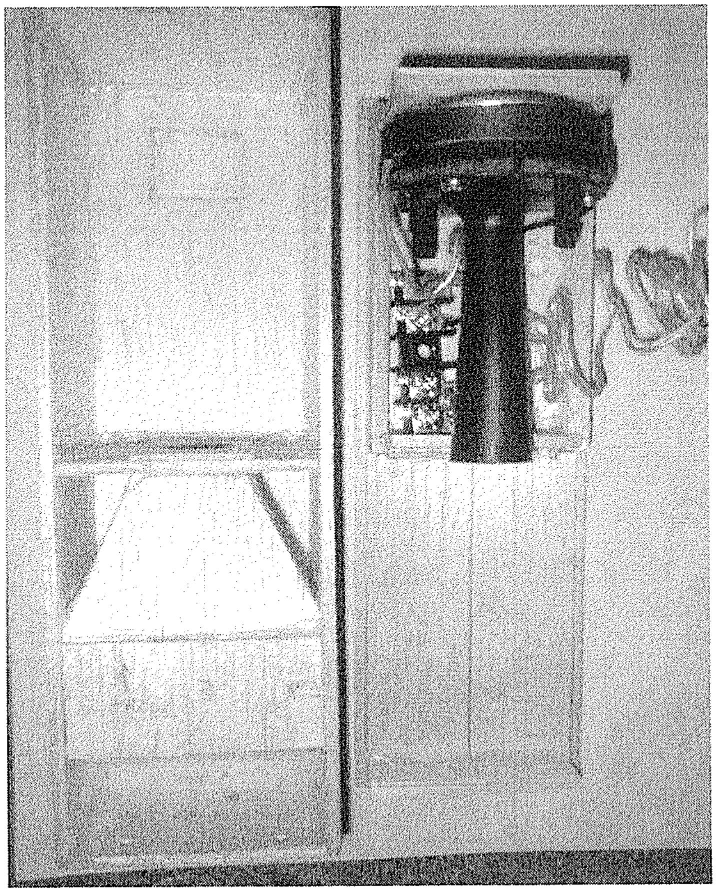


Figure 6.5: Cardboard model of the proposed speaker box

The sound duct is designed in a slightly inclined 'L' shape in a way to avoid the snow or rain water from entering the speaker box. This rectangular shape of the duct is also designed to control the dispersion of sound to some extent to help reduce the confusion caused by the speaker tones at other pedestrian crosswalks or other intersections in the neighborhood. The detailed parts' drawings for the proposed Audible traffic signal speaker are presented in Appendix 5.

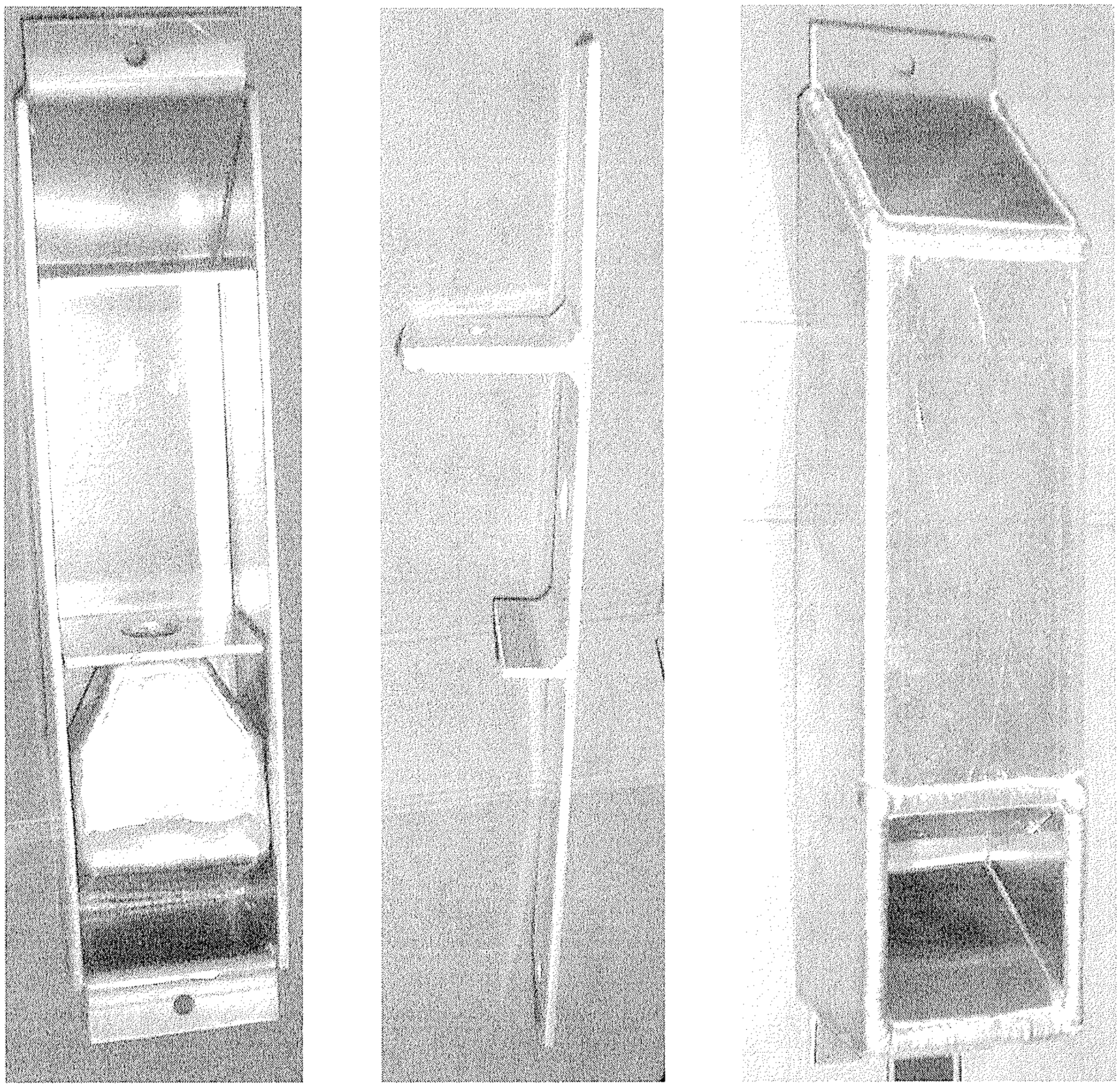
6.3 Materials and Fabrication

As this speaker will be installed outdoors, the enclosure needs to be very strong; vandal proof and weather proof. Hence a 3 mm-thick sheet of Marine Grade Aluminum 6061-27 is used. The box consists of two parts:

a) The cover where the rectangular sound duct is welded in alignment with the opening on the speaker box (Figure 6.6 a).

b) The base plate on which the horn is mounted with a 20 mm hole at the center of the plate for the conduit (Figure 6.6 b).

A perfect assembly of the cover with the base plate secures the coupling of the conical horn with the rectangular duct. Refer to the figures A1 to A3 in Appendix 5 for detailed part drawings.



(a) Cover (b) Base (c) Base + Cover assembly

Figure 6.6 – Speaker box prototype manufactured at Enduron Inc., Winnipeg

Upon requesting price estimates for manufacturing the designed speaker to three machine shops, two quotations have been received. The quotation that had the lowest price and full compliance to the specification was from a machine shop "Enduron Custom Inc.", Winnipeg, Manitoba.

The speaker box prototype samples were required to be manufactured using aluminum alloys. Hence, and based on its design and manufacturing capabilities concerning special metal alloys and best quotation received, Enduron Custom Inc. of Winnipeg has been chosen to produce the samples. After these units are delivered, they were tested for their efficiency in the real traffic conditions to re-evaluate and analyze their capability to handle the current issues discussed in the first chapter. The proposed speaker successfully passed all the tests and the traffic department of the city of Winnipeg has approved the design with minor modifications for ease of mounting them on the pole and ordered Enduron Custom Inc. for manufacturing 200 units for actual usage in the city.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 Overview

In chapter 4 the analysis and its conclusions were already discussed in depth for each issue specifically. This chapter summarizes the same results in a more generalized manner rather than being specific. Recalling the objective of the research, the focus of the experimental design is to investigate the effect and the interaction of the main factor 'Speaker height' versus various other factors such as 'Season', 'Activation system', 'No. of street lanes' and 'Existence of high-rise buildings'. Knowing which factors affect the audible traffic system, guidelines can now be set for designing and re-configuring the Audible Traffic Signals. The testing undertaken at the four selected intersections provided a lot of insight into how much impact speaker height has on the overall performance of the audible pedestrian signal system. It was discovered that locating the speaker at four feet helped pedestrians better understand, locate the crossing point and cross the streets. Other key recommendations included changing the timing of the crossing tones versus locating tones to match 'walk' and 'don't walk' signs; consistent installation and maintenance of intersections to ensure better accessibility. A new speaker box was designed based on the exponential loudspeaker horn which met all goals – the control of sound to diminish neighborhood disturbance, and was durable enough to withstand Winnipeg weather & possible vandalism.

7.2 Locating Tones

From the tests performed on the locating tones, it was clear that lowering the speaker height from 10 feet to 4 feet provided a marked improvement in the overall performance of the locator tones for all of the tested intersections. This is because the sound (or tone) from the speakers placed at 10 feet height is allowed to propagate over a larger radius reflecting off several surfaces becoming severely diffused resulting in a poor differentiation between direct and reflected sound. This becomes even worse during winter when the cold air is much denser compared to that in summer. For the ear to be able to sense the location of an emitting tone there must be a discernable amount of direct sound from the speaker that reaches the ear before any reflections do. A poor sense of the speaker location shall result if such a differentiation cannot be made by the brain. When looking at the effect of the other variables, the only factor that appeared to have any major influence on the results was the season. Moreover as it has been noted from section 4.2 that reducing the speaker height to 4 feet is reducing the difference between the performances of a non-PB to that is a PB system.

7.3 Crossing Tones

When observing the results obtained for crossing tone performance, it was concluded that all tested intersections benefited from the lowering of the speakers to 4', although the margin of improvement was quite small in all cases. The other factors that had major influence on the results were intersection size & complexity and season. However, when considering the effect of lowering the speaker height to

4', very little difference in improvement was evident between the large and small intersections. As a result, the lower 4' setting did little to eliminate the effect of intersection size and complexity on the performance of the crossing tones.

7.4 Activation System

Although a thorough analysis is not done on the activation system it can still be argued that the activation tone worked far better at 4' when compared to 10', since the tone is heard when the pedestrian is standing right next to the pole, it makes sense that the tone emitted at 4' is more easily heard than the one at 10', as the 4' speaker is located closer to the ear. Due to the localized use of the activation tone around the pole, consideration of the effects of intersection size and complexity do not matter very much.

7.5 Crossing Tone Duration

As most of the push button systems in the city currently run the crossing tones for maximum 7 seconds at which point the locating tone is reactivated, it is recommended that the crossing tones and subsequent locating tones be integrated with the 'Walk' and 'Don't Walk' signs so that visually impaired pedestrians are able to get a sense of how much time they have to cross the intersection. This way, the visually impaired pedestrians will be getting as much information about the lights as all other pedestrians do by watching the 'Walk' and 'Don't Walk' signs.

Another way to let the pedestrians know how much time they have, the controller can be programmed in such a way that the timing and duration of the *tone notes* to decrease in 2 or 3 stages as the time approaches the finish stage. For example if the total tone duration programmed for a particular street is 18 seconds then split this duration into 3 stages such that for first 6 six seconds the tone will have a *note* duration of 500 ms with a pause of 100 ms, for the next six seconds the tone will have a *note* duration of 250 ms with a pause of 50 ms and for the final stage of six seconds the tone will have a *note* duration of 100 ms with a pause of 20 ms and when the time is ended then it should be indicated with a continuous tone for about 3 to 5 seconds.

7.6 Future Research

Audible traffic signals, itself is a wide subject to deal with, surrounded with various topics. In this research potential solutions were suggested by reducing the speaker height to handle the current issues. But with today's increasing traffic and the sound pollution caused by it, have become more important to tackle with ambient sounds. As such, additional research should be conducted on location tones and crossing tones to clarifying a relation with the ambient / traffic noise.

In view of the annoyance caused by the audible signals in the neighborhood, a new type / shaped speaker was designed in this research project to limit the dispersion of sound and reducing the problem to some extent. However an in-depth research on acoustics engineering should be conducted emphasizing on the speaker shapes to design a speaker that would work precisely within a certain range of the intersection.

A few issues were discussed in chapter 5 and potential solutions also were suggested. To deal with the problem of Localization of blind spot concerning the pedestrians' orientation while crossing the streets, the use of alternating tones at the two speakers has been recommended. Secondly, the problem of far and near effect concerning a pedestrian's sense of distance also has been discussed. It followed with the recommendation that the auto-volume sensors at the four corners of an intersection be coordinated so that one does not have the ability to overpower the others. Before implementing these recommendations, a further in-depth research on these two issues could be conducted with a possibility of providing and testing alternative solutions suitable and feasible for the local conditions.

Voice activated systems or talking signals are a growing trend in many parts of North America. Voice activated systems transmit voice messages with orientation information through an infrared wireless communications system or by a push button, etc. Further research on the use of these kinds of systems for pedestrian signals can be worth undertaking for future considerations.

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APPENDIX 1

Consent form for data collection

DESIGN AND CONFIGURATION OF AUDIBLE TRAFFIC SIGNALS

Dr. Tarek ElMekkawy
Department of Mechanical and Manufacturing Engineering
University of Manitoba
Sponsored by the City of Winnipeg

The consent form will be read to the subject by the research student. This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information. This document is also available in alternative formats for your convenience.

The current locations and designs of audible signals allegedly cause a variety of barriers for persons living in the community both with and without visual impairments. Traffic Signals Division of Public Works Department is limited to audible pedestrian signals that are commercially available:

GOAL:

To identify the best available audible pedestrian signal technology that will meet community usability needs. The identified technology will take into consideration reasonable costs and Winnipeg's variable weather conditions through four seasons.

During the experiments of locating the pole you will begin one half block before the intersection and use your own method in reaching the pole. The researcher will designate a person to follow you at a close enough distance to protect you. In this experiment you will not cross the street because the objective is to test the ease of locating the push button pole. Every person will give there feedback through a general questionnaire that will be discussed with you.

During the second set of experiments, you have to cross the street. In order to ensure your safety, a designated person will follow you at a close enough distance but far enough not to distract you. as an indication of your decision to cross the intersection, you will raise your hand right before deciding to cross the street for enough time (2-3 seconds) for the designated person to notice you. If you are taking an incorrect decision, the designated person will warn you. In addition, if the subject loses his orientation during the crossing process, the designated person will assist you cross the street to a safe location. At the end of the experiments, you will be asked questions concerning the experiment. These questions will be read to you by a research student. In addition, the research student will be responsible for writing your answers to these questions. You are also encouraged to make any comments you wish concerning any part of the experiment. The experiments will be recorded using video camera. It's not planned to show that video tapes to anyone excluding the principal investigator and the students who will be involved in the analysis and system design process. These video tapes will not be published. And they will be stored in the principal investigator's office for one year starting from the ending time of the project and then destroyed.

All information collected during the course of this research will be kept confidential in the principal investigator's office for one year staring from the end of the project then all the collected information will be destroyed. No Names will be mentioned in the results of the research. Each consent form will be assigned a numeric value with the principle investigator maintaining the only record of each consent form. All results of this study will be made public through the City of Winnipeg Access Advisory Committee.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any question you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation (Dr. Tarek ElMekkawy,)

This research has been approved by the [REB:]. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122, or e-mail margaret_bowman@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

____

Participant's Name   Participant's Signature   Date (dd/mm/yy)

____

Researcher and/or Delegate's Signature   Date (dd/mm/yy

____

Researcher and/or Delegate's Signature   Date (dd/mm/yy)

APPENDIX 2

Questionnaire Form

Date : ____________________

Intersection: ____________________

Direction: N/S ☐ E/W ☐

Subject ID Number: ______________

Pole Location:

Initial Data:

- Height: _______________
- Tone : ________________
- Weather Conditions: ____

Volunteer Feedback: *Push Button Style System*

- Describe the tone's ability to allow location of the crossing point

  1 2 3 4 5 6 7 8 9 10

- Is the pole adequately close to the crossing point?

  1 2 3 4 5 6 7 8 9 10

- Push Button:
  - Rate the Holding time – 1 for poor, 10 for best

    1 2 3 4 5 6 7 8 9 10

  - Did you hear the activation noise?

    1 2 3 4 5 6 7 8 9 10

  - What noise did you hear? ______________________________________

- Was the path to the pole obstructed?

  1 2 3 4 5 6 7 8 9 10

  - Please explain ____

- Did the weather affect your ability to locate the crossing point?

  1 2 3 4 5 6 7 8 9 10

  - Please explain ____

Additional Comments: ____

____

Volunteer Feedback: *Non-Push Button Style System*

- How did you locate the crossing point?

  Crossing Tone ☐ Traffic Noise ☐ Both ☐

- Were the above methods adequate to locate the crossing point?

  1 2 3 4 5 6 7 8 9 10

- Was the speaker pole adequately close to the crossing point?

  1 2 3 4 5 6 7 8 9 10

- Additional Comments: ____

____

____.

____

____.

____

____.

- Test Coordinator Observations: __________________________________

____

____.

____

____.

____

____.

Street Crossing:

- Height_______________
- Tone: _______________
- Crossway length: _______________
- Crossway length: _______________
- Weather Conditions: ____

Volunteer Feedback:

- Describe the tones ability to help you locate the opposite end of the crossway:

  1 2 3 4 5 6 7 8 9 10
- Tone Volume

  1 2 3 4 5 6 7 8 9 10
  - Could you hear the tone at all times while crossing the streets?

    1 2 3 4 5 6 7 8 9 10
  - Did the tones volume vary as you crossed the street?

    1 2 3 4 5 6 7 8 9 10
  - Explain____
- Did you lose you sense of direction at any point while crossing the street?

  1 2 3 4 5 6 7 8 9 10
- Did the tone last long enough for you to safely cross the intersection?

  1 2 3 4 5 6 7 8 9 10
- Did the weather affect your ability to cross the street?

  1 2 3 4 5 6 7 8 9 10
  - Explain
- Additional Comments : ____

APPENDIX 3

Tabulated Data from the Feedback Form

Season	Speaker Height (Ft.)	INTERSECTION ALL DIRECTIONS (N/S, E/W)	the crossing point		the other end of the	10. Tone volume - heard	through-out crossing?	11. Tone volume - varied	while crossing?	at any point while crossing	?	sufficient to cross the	street?
Season	Spr.Ht	Intersection	1N	1E	9N	9E	10N	10E	11N	11E	12N	12E	13N	13E
Summer	10 ft	Broadway + Fort	5	5	3	5	3	5	1	1	10	10	1	10
Summer	10 ft	Broadway + Fort	5	3	4	6	8	8	8	8	7	6	5	8
Summer	10 ft	Broadway + Fort	8	8	2	2	2	2	9	9	10	10	4	10
Summer	10 ft	Broadway + Fort	10	10	3	5	2	4	5	5	10	10	10	10
Summer	10 ft	Broadway + Fort	5	5	7	9	7	9	7	8	9	9	9	6
Summer	10 ft	Broadway + Fort	10	10	10	10	10	10	8	8	10	10	10	10
Summer	10 ft	Broadway + Fort	2	5	6	4	8	8	6	6	4	4	6	6
Summer	10 ft	Broadway + Fort	1	7	2	9	2	10	8	3	1	1	2	10
Summer	10 ft	Broadway + Fort	1	1	1	1	1	1	1	1	5	8	1	7
Summer	10 ft	Broadway + Fort	7	7	7	7	8	8	6	6	9	9	4	4
Summer	10 ft	Donald + York	8	8	6	6	6	7	6	7	9	9	7	7
Summer	10 ft	Donald + York	7	8	4	5	5	8	4	7	7	9	10	10
Summer	10 ft	Donald + York	10	10	10	5	10	5	10	10	10	10	10	10

Summer	10 ft	Donald + York	10	10	10	10	9	9	10	9	10	10	9	9
Summer	10 ft	Donald + York	10	10	9	9	10	10	10	10	10	10	10	10
Summer	10 ft	Donald + York	8	8	4	4	10	10	10	10	8	10	10	10
Summer	10 ft	Donald + York	8	8	1	1	1	1	1	1	8	3	1	1
Summer	10 ft	Donald + York	8	8	6	6	7	7	7	7	8	8	6	6
Summer	10 ft	Donald + York	10	10	6	8	6	9	5	3	1	1	10	10
Summer	10 ft	Donald + York	10	10	3	7	2	10	2	5	10	10	2	10
Summer	10 ft	Smith + York	8	8	8	8	7	9	8	8	9	9	9	9
Summer	10 ft	Smith + York	5	5	4	7	10	10	9	9	10	10	10	10
Summer	10 ft	Smith + York	9	9	7	8	9	9	7	8	9	9	10	10
Summer	10 ft	Smith + York	8	8	9	9	9	9	7	7	7	7	9	9
Summer	10 ft	Smith + York	10	10	10	10	10	10	10	10	10	10	10	10
Summer	10 ft	Smith + York	8	8	8	6	10	10	8	8	4	6	10	10
Summer	10 ft	Smith + York	10	10	10	10	10	10	1	1	10	10	10	10
Summer	10 ft	Smith + York	8	8	8	8	10	10	10	10	10	10	10	10
Summer	10 ft	Smith + York	3	3	1	5	1	1	1	1	10	10	1	1
Summer	10 ft	St. Annes + Worthington	10	10	10	1	10	1	5	5	10	2	10	10
Summer	10 ft	St. Annes + Worthington	10	6	8	8	9	8	9	8	8	8	10	6
Summer	10 ft	St. Annes + Worthington	10	3	10	7	10	4	1	1	1	1	10	3
Summer	10 ft	St. Annes + Worthington	1	1	1	1	1	1	1	1	10	10	1	1
Summer	10 ft	St. Annes + Worthington	2	2	6	3	5	2	4	4	7	7	5	2
Summer	10 ft	St. Annes + Worthington	2	2	2	2	10	6	5	5	10	10	9	3

Summer	10 ft	St. Annes + Worthington	9	9	10	10	10	7	10	10	10	10	8	8
Summer	10 ft	St. Annes + Worthington	6	6	6	6	10	10	8	6	8	4	10	10
Summer	4 ft	Broadway + Fort	7	7	4	4	7	7	7	7	9	9	8	8
Summer	4 ft	Broadway + Fort	8	8	9	9	9	9	7	7	10	10	8	8
Summer	4 ft	Broadway + Fort	8	8	3	3	4	4	10	10	10	10	3	3
Summer	4 ft	Broadway + Fort	8	8	5	5	5	5	4	4	10	10	6	6
Summer	4 ft	Broadway + Fort	1	1	6	6	9	9	10	10	5	5	10	10
Summer	4 ft	Broadway + Fort	1	1	4	4	5	5	5	5	9	9	3	3
Summer	4 ft	Broadway + Fort	9	1	8	7	8	7	9	8	9	9	1	9
Summer	4 ft	Donald + York	10	10	10	10	10	10	8	8	9	9	10	10
Summer	4 ft	Donald + York	8	8	8	8	8	8	6	6	8	8	7	7
Summer	4 ft	Donald + York	4	4	1	1	10	10	10	10	10	10	10	10
Summer	4 ft	Donald + York	3	7	2	2	7	7	5	5	10	10	8	8
Summer	4 ft	Donald + York	2	7	8	8	5	5	5	5	9	9	4	7
Summer	4 ft	Donald + York	10	10	10	7	7	7	6	6	10	10	10	10
Summer	4 ft	Donald + York	8	8	8	8	8	8	6	8	6	8	8	8
Summer	4 ft	Donald + York	8	8	5	8	9	9	7	7	9	9	10	10
Summer	4 ft	Donald + York	10	10	8	10	10	10	8	9	9	9	10	10
Summer	4 ft	Donald + York	10	10	9	9	9	9	10	10	9	9	10	10
Summer	4 ft	Donald + York	10	10	5	5	6	6	10	10	5	9	10	10
Summer	4 ft	Smith + York	9	9	9	9	9	9	7	7	9	9	9	9
Summer	4 ft	Smith + York	10	10	10	9	10	6	10	6	10	10	10	10

Summer	4 ft	Smith + York	8	8	8	8	8	4	8	4	8	4	8	8
Summer	4 ft	Smith + York	7	7	8	8	9	9	7	7	10	10	9	9
Summer	4 ft	Smith + York	10	10	9	9	10	10	10	10	10	10	10	10
Summer	4 ft	Smith + York	8	8	8	8	8	10	10	10	6	8	10	10
Summer	4 ft	Smith + York	7	7	7	7	8	8	5	5	7	7	9	9
Summer	4 ft	Smith + York	5	5	9	7	9	2	7	7	9	9	10	10
Summer	4 ft	Smith + York	10	10	10	9	10	6	9	9	9	9	10	10
Summer	4 ft	Smith + York	10	10	10	2	10	10	5	5	10	10	10	10
Summer	4 ft	St. Annes + Worthington	7	5	6	3	3	3	9	9	9	9	3	3
Summer	4 ft	St. Annes + Worthington	5	5	2	2	2	2	8	8	3	8	9	9
Summer	4 ft	St. Annes + Worthington	6	6	1	1	3	1	9	9	8	8	8	8
Summer	4 ft	St. Annes + Worthington	1	1	1	1	3	3	8	8	9	9	1	1
Summer	4 ft	St. Annes + Worthington	7	7	6	7	8	8	7	5	9	9	9	8
Summer	4 ft	St. Annes + Worthington	8	8	6	6	8	8	7	7	8	8	3	3
Summer	4 ft	St. Annes + Worthington	2	2	2	2	8	8	9	9	10	10	5	5
Winter	10 ft	Broadway + Fort	1	1	1	1	1	1	10	10	1	1	1	1
Winter	10 ft	Broadway + Fort	1	1	1	10	1	7	10	8	10	1	1	2
Winter	10 ft	Broadway + Fort	4	3	2	7	2	10	7	2	1	1	1	10
Winter	10 ft	Broadway + Fort	3	3	0	0	9	9	1	1	1	1	8	10
Winter	10 ft	Broadway + Fort	9	9	1	7	10	5	1	1	3	1	1	6
Winter	10 ft	Donald + York	6	6	7	7	10	10	5	5	1	1	10	10
Winter	10 ft	Donald + York	4	4	3	3	10	10	1	9	1	1	10	10

Winter	10 ft	Donald + York	7	7	5	7	8	10	1	3	1	1	10	10
Winter	10 ft	Donald + York	10	10	8	7	10	10	8	1	1	1	10	10
Winter	10 ft	Donald + York	10	10	10	10	10	10	1	1	1	1	7	10
Winter	10 ft	Donald + York	9	9	8	8	8	8	3	3	1	1	9	9
Winter	10 ft	Donald + York	7	7	7	9	10	10	1	1	1	1	10	10
Winter	10 ft	Donald + York	9	9	9	9	10	10	1	1	1	1	10	10
Winter	10 ft	Smith + York	5	5	10	10	9	9	6	5	1	1	10	10
Winter	10 ft	Smith + York	3	3	2	2	2	3	9	10	1	1	10	10
Winter	10 ft	Smith + York	9	9	7	6	8	7	1	2	1	1	8	7
Winter	10 ft	Smith + York	9	9	10	10	10	10	1	1	1	1	10	10
Winter	10 ft	Smith + York	5	5	10	5	10	5	1	1	10	5	10	5
Winter	10 ft	St. Annes + Worthington	1	1	3	2	4	1	8	3	1	1	5	1
Winter	10 ft	St. Annes + Worthington	6	3	9	6	9	6	1	1	1	1	10	7
Winter	10 ft	St. Annes + Worthington	10	10	10	9	10	5	1	1	1	1	10	9
Winter	10 ft	St. Annes + Worthington	1	1	10	10	10	6	1	1	1	1	6	5
Winter	10 ft	St. Annes + Worthington	7	2	8	5	5	5	3	3	1	1	9	9
Winter	10 ft	St. Annes + Worthington	3	3	9	8	8	5	1	1	4	3	9	9
Winter	4 ft	Broadway + Fort	10	10	2	10	1	10	9	9	9	9	1	10
Winter	4 ft	Broadway + Fort	6	9	6	10	3	10	5	9	9	9	3	10
Winter	4 ft	Broadway + Fort	10	10	10	10	10	10	9	9	9	9	10	10
Winter	4 ft	Broadway + Fort	10	10	7	10	5	10	9	9	9	9	5	10
Winter	4 ft	Broadway + Fort	10	10	10	10	3	10	9	9	9	9	10	10

Winter	4 ft	Donald + York	10	10	8	10	10	10	8	8	9	9	10	10
Winter	4 ft	Donald + York	10	10	8	9	8	9	9	10	9	9	8	10
Winter	4 ft	Donald + York	10	10	9	10	10	10	8	9	9	9	10	10
Winter	4 ft	Donald + York	8	8	8	10	10	10	9	9	9	9	10	10
Winter	4 ft	Donald + York	10	10	8	9	10	10	9	9	9	9	10	10
Winter	4 ft	Donald + York	9	9	10	10	10	10	6	9	9	9	10	10
Winter	4 ft	Smith + York	10	10	6	8	10	10	6	8	9	9	10	10
Winter	4 ft	Smith + York	9	9	7	8	7	10	9	9	9	9	7	10
Winter	4 ft	Smith + York	10	10	9	7	9	8	8	7	9	9	10	10
Winter	4 ft	Smith + York	10	10	9	9	10	10	9	9	9	9	10	10
Winter	4 ft	Smith + York	8	8	8	8	10	10	9	9	9	9	10	10
Winter	4 ft	Smith + York	10	10	9	9	10	10	10	10	10	10	10	10
Winter	4 ft	Smith + York	9	9	8	9	7	8	8	8	9	9	10	10
Winter	4 ft	St. Annes + Worthington	9	9	9	9	3	3	9	9	9	9	3	3
Winter	4 ft	St. Annes + Worthington	6	9	7	3	7	3	9	9	9	9	9	9
Winter	4 ft	St. Annes + Worthington	8	8	9	9	9	9	9	9	9	9	10	10
Winter	4 ft	St. Annes + Worthington	8	8	6	6	3	3	9	9	9	9	3	3

APPENDIX 4.1

ANOVA for Experiment # 1 from MINITAB®

General Linear Model: Crossing Point Location (CPL) Ability versus Season, Speaker Height, Push button and presence of High rise building at the corners.

Factor	Type	Levels	Values
Season	fixed	2	Summer, Winter
Spkr Ht	fixed	2	10 ft, 4 ft
PushButton	fixed	2	N, Y
Highrise	fixed	2	N, Y

Analysis of Variance for CPL Ability, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Season	1	2.930	4.582	4.582	0.82	0.369
Spkr Ht	1	55.947	82.411	82.411	14.67	0.000
PushButton	1	178.008	152.450	152.450	27.13	0.000
Highrise	1	0.036	0.397	0.397	0.07	0.791
Season*Spkr Ht	1	100.496	111.700	111.700	19.88	0.000
Season*PushButton	1	3.860	5.113	5.113	0.91	0.342
Season*Highrise	1	0.453	0.116	0.116	0.02	0.886
Spkr Ht*PushButton	1	6.055	8.660	8.660	1.54	0.217
Spkr Ht*Highrise	1	10.866	11.988	11.988	2.13	0.147
PushButton*Highrise	1	8.010	6.602	6.602	1.17	0.281
Season*Spkr Ht*PushButton	1	14.736	14.075	14.075	2.51	0.117
Season*Spkr Ht*Highrise	1	0.512	0.810	0.810	0.14	0.705
Season*PushButton*Highrise	1	0.389	0.460	0.460	0.08	0.775
Spkr Ht*PushButton*Highrise	1	1.031	0.504	0.504	0.09	0.765
Season*Spkr Ht*PushButton*Highrise	1	1.502	1.502	1.502	0.27	0.606
Error	102	573.112	573.112	5.619		
Total	117	957.943				

S = 2.37039   R-Sq = 40.17%   R-Sq(adj) = 31.37%

Unusual Observations for CPL Ability

Obs	CPL Ability	Fit	SE Fit	Residual	St Resid	
19	3.0000	7.6667	0.7901	-4.6667	-2.09	R
28	1.0000	5.7500	0.7496	-4.7500	-2.11	R
30	10.0000	5.5625	0.8381	4.4375	2.00	R
33	1.0000	5.5625	0.8381	-4.5625	-2.06	R
63	1.0000	5.4286	0.8959	-4.4286	-2.02	R
64	1.0000	5.4286	0.8959	-4.4286	-2.02	R
90	9.0000	3.5000	1.0601	5.5000	2.59	R
93	10.0000	4.0000	0.9677	6.0000	2.77	R

R denotes an observation with a large standardized residual.

General Linear Model: Crossing Point Location (CPL) Ability versus Season, Speaker Height, Push button and presence of High rise building at the corners.

Factor	Type	Levels	Values
Season	fixed	2	Summer, Winter
Spkr Ht	fixed	2	10 ft, 4 ft
PushButton	fixed	2	N, Y
Highrise	fixed	2	N, Y

Analysis of Variance for CPL Ability, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Season	1	0.637	1.860	1.860	0.50	0.480
Spkr Ht	1	64.911	114.691	114.691	31.06	0.000
PushButton	1	155.128	152.821	152.821	41.39	0.000
Highrise	1	3.205	1.149	1.149	0.31	0.579
Season*Spkr Ht	1	118.969	128.623	128.623	34.83	0.000
Season*PushButton	1	0.163	0.271	0.271	0.07	0.787
Season*Highrise	1	4.581	4.933	4.933	1.34	0.251
Spkr Ht*PushButton	1	24.775	30.848	30.848	8.35	0.005
Spkr Ht*Highrise	1	12.476	14.853	14.853	4.02	0.048
PushButton*Highrise	1	16.614	11.639	11.639	3.15	0.079
Season*Spkr Ht*PushButton	1	16.664	16.621	16.621	4.50	0.037
Season*Spkr Ht*Highrise	1	0.316	0.300	0.300	0.08	0.776
Season*PushButton*Highrise	1	0.256	0.266	0.266	0.07	0.789
Spkr Ht*PushButton*Highrise	1	0.321	0.338	0.338	0.09	0.763
Season*Spkr Ht*PushButton*Highrise	1	0.017	0.017	0.017	0.00	0.945
Error	94	347.105	347.105	3.693		
Total	109	766.139				

S = 1.92162   R-Sq = 54.69%   R-Sq(adj) = 47.46%

Least Squares Means for CPL Ability

Season	Mean	SE Mean
Summer	7.202	0.2446
Winter	6.929	0.2976
Spkr Ht		
10 ft	5.992	0.2715
4 ft	8.139	0.2732
PushButton		
N	8.304	0.2462
Y	5.826	0.2962
Highrise		
N	6.958	0.2677
Y	7.173	0.2769

APPENDIX 4.2

ANOVA for Experiment # 2 from MINITAB®

General Linear Model: Tone ability versus Season, Spkr Ht, HR

Factor	Type	Levels	Values
Season	fixed	2	Summer, Winter
Spkr Ht	fixed	2	10 ft, 4 ft
HR	fixed	2	N, Y

Analysis of Variance for Tone ability, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Season	1	18.304	14.463	14.463	5.36	0.022
Spkr Ht	1	209.988	282.773	282.773	104.76	0.000
HR	1	7.564	1.822	1.822	0.68	0.412
Season*Spkr Ht	1	140.880	143.978	143.978	53.34	0.000
Season*HR	1	4.197	4.144	4.144	1.54	0.217
Spkr Ht*HR	1	0.972	1.055	1.055	0.39	0.533
Season*Spkr Ht*HR	1	0.087	0.087	0.087	0.03	0.858
Error	228	615.445	615.445	2.699		
Total	235	997.436				

S = 1.64296   R-Sq = 38.30%   R-Sq(adj) = 36.40%

Unusual Observations for Tone ability

Obs	Tone ability	Fit	SE Fit	Residual	St Resid	
3	10.0000	6.6042	0.2738	3.3958	2.10	R
7	2.7500	6.6042	0.2738	-3.8542	-2.38	R
14	3.2500	6.6042	0.2738	-3.3542	-2.07	R
17	10.0000	6.6042	0.2738	3.3958	2.10	R
25	1.5000	6.6042	0.2738	-5.1042	-3.15	R
29	2.2500	6.6042	0.2738	-4.3542	-2.69	R
31	3.2500	6.6042	0.2738	-3.3542	-2.07	R
32	3.2500	6.6042	0.2738	-3.3542	-2.07	R
44	3.2500	6.9605	0.2665	-3.7105	-2.29	R
45	2.0000	6.9605	0.2665	-4.9605	-3.06	R
55	3.2500	6.9605	0.2665	-3.7105	-2.29	R
64	2.7500	6.9605	0.2665	-4.2105	-2.60	R
87	3.7500	7.1528	0.2739	-3.4028	-2.10	R
182	7.7500	4.5250	0.3674	3.2250	2.01	R
213	5.2500	8.5729	0.3354	-3.3229	-2.07	R

R denotes an observation with a large standardized residual.

General Linear Model: Tone ability versus Season, Spkr Ht, HR

Factor	Type	Levels	Values
Season	fixed	2	Summer, Winter
Spkr Ht	fixed	2	10 ft, 4 ft
HR	fixed	2	N, Y

Analysis of Variance for Tone ability, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Season	1	39.677	32.656	32.656	17.86	0.000
Spkr Ht	1	166.159	234.869	234.869	128.45	0.000
HR	1	7.734	1.511	1.511	0.83	0.364
Season*Spkr Ht	1	187.969	192.227	192.227	105.13	0.000
Season*HR	1	4.108	3.954	3.954	2.16	0.143
Spkr Ht*HR	1	1.100	1.577	1.577	0.86	0.354
Season*Spkr Ht*HR	1	1.368	1.369	1.368	0.75	0.388
Error	213	389.470	389.470	1.828		
Total	220	797.585				

S = 1.35222   R-Sq = 51.17%   R-Sq(adj) = 49.56%

Least Squares Means for Tone ability

Season	Mean	SE Mean
Summer	7.377	0.1184
Winter	6.589	0.1441
Spkr Ht		
10 ft	5.926	0.1323
4 ft	8.040	0.1316
HR		
N	6.898	0.1304
Y	7.068	0.1334

Interaction Plot (data means) for Tone ability

APPENDIX 4.3

ANOVA FOR EXPERIMENT # 3 FROM MINITAB®

General Linear Model: Tone Duration versus Season, Spkr Ht, Lanes

```
Factor   Type   Levels  Values
Season   fixed       2  Summer, Winter
Spkr Ht  fixed       2  10 ft, 4 ft
Lanes    fixed       4  2, 4, 6, 8


Analysis of Variance for Tone Duration, using Adjusted SS for Tests

Source                  DF    Seq SS    Adj SS   Adj MS      F      P
Season                   1    19.559     2.601    2.601   0.40  0.529
Spkr Ht                  1    18.278     0.113    0.113   0.02  0.896
Lanes                    3   514.280   530.786  176.929  26.98  0.000
Season*Spkr Ht           1     5.659     6.273    6.273   0.96  0.329
Season*Lanes             3    25.658    24.826    8.275   1.26  0.288
Spkr Ht*Lanes            3    58.217    60.528   20.176   3.08  0.028
Season*Spkr Ht*Lanes     3    10.744    10.744    3.581   0.55  0.651
Error                  220  1442.740  1442.740    6.558
Total                  235  2095.136


S = 2.56084   R-Sq = 31.14%   R-Sq(adj) = 26.44%


Unusual Observations for Tone Duration

        Tone
Obs  Duration     Fit  SE Fit  Residual  St Resid
  4    1.0000  7.8750  0.9054   -6.8750     -2.87 R
 15    1.0000  8.2708  0.3696   -7.2708     -2.87 R
 18    2.0000  8.2708  0.3696   -6.2708     -2.47 R
 27    1.0000  8.2708  0.3696   -7.2708     -2.87 R
 44    1.0000  8.2708  0.3696   -7.2708     -2.87 R
 56    1.0000  8.2708  0.3696   -7.2708     -2.87 R
105    3.0000  8.8571  0.3658   -5.8571     -2.31 R
108    3.0000  8.8571  0.3658   -5.8571     -2.31 R
164    1.0000  8.8387  0.4599   -7.8387     -3.11 R
165    2.0000  8.8387  0.4599   -6.8387     -2.71 R
182    1.0000  6.6667  1.0455   -5.6667     -2.42 R
191    8.0000  2.4000  1.1452    5.6000      2.44 R
193    3.0000  6.2500  1.2804   -3.2500     -1.47 X
194    9.0000  6.2500  1.2804    2.7500      1.24 X
195   10.0000  6.2500  1.2804    3.7500      1.69 X
196    3.0000  6.2500  1.2804   -3.2500     -1.47 X
228    3.0000  6.2500  1.2804   -3.2500     -1.47 X
229    9.0000  6.2500  1.2804    2.7500      1.24 X
230   10.0000  6.2500  1.2804    3.7500      1.69 X
231    3.0000  6.2500  1.2804   -3.2500     -1.47 X
232    1.0000  5.8000  1.1452   -4.8000     -2.10 R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Tone Duration versus Season, Spkr Ht, Lanes

Factor	Type	Levels	Values
Season	fixed	2	Summer, Winter
Spkr Ht	fixed	2	10 ft, 4 ft
Lanes	fixed	4	2, 4, 6, 8

Analysis of Variance for Tone Duration, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Season	1	17.944	22.969	22.969	9.14	0.003
Spkr Ht	1	4.743	2.186	2.186	0.87	0.352
Lanes	3	871.177	813.737	271.246	107.96	0.000
Season*Spkr Ht	1	10.114	16.826	16.826	6.70	0.010
Season*Lanes	3	62.259	57.647	19.216	7.65	0.000
Spkr Ht*Lanes	3	35.794	20.431	6.810	2.71	0.046
Season*Spkr Ht*Lanes	3	26.430	26.430	8.810	3.51	0.016
Error	191	479.867	479.867	2.512		
Total	206	1508.329				

S = 1.58505   R-Sq = 68.19%   R-Sq(adj) = 65.69%

Least Squares Means for Tone Duration

Season	Mean	SE Mean
Summer	5.823	0.2212
Winter	6.863	0.2634
Spkr Ht		
10 ft	6.503	0.2125
4 ft	6.182	0.2704
Lanes		
2	8.149	0.3915
4	9.346	0.1322
6	5.221	0.3689
8	2.655	0.4079

APPENDIX 5

Detailed Parts' Drawings for the Speaker

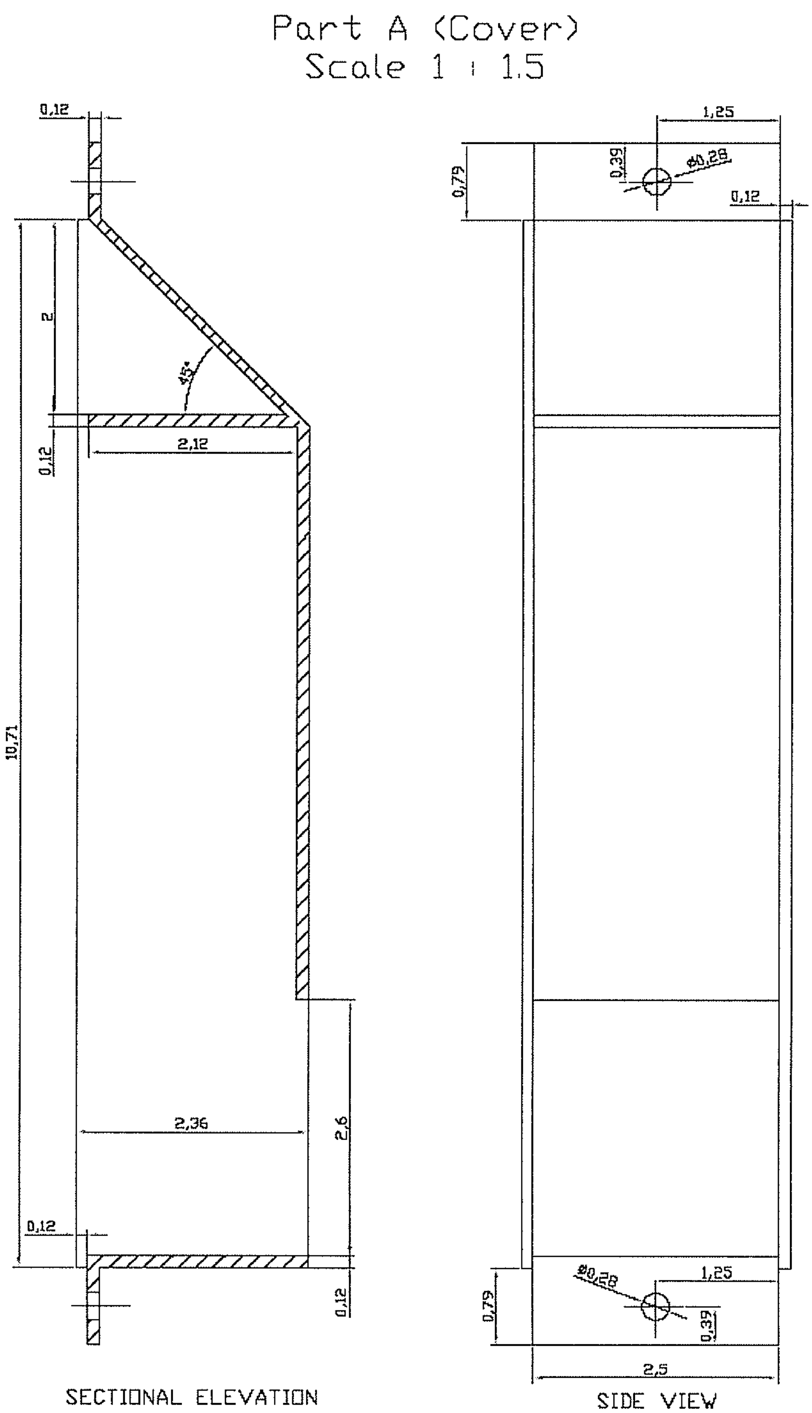

Figure A1: Part A (Cover)

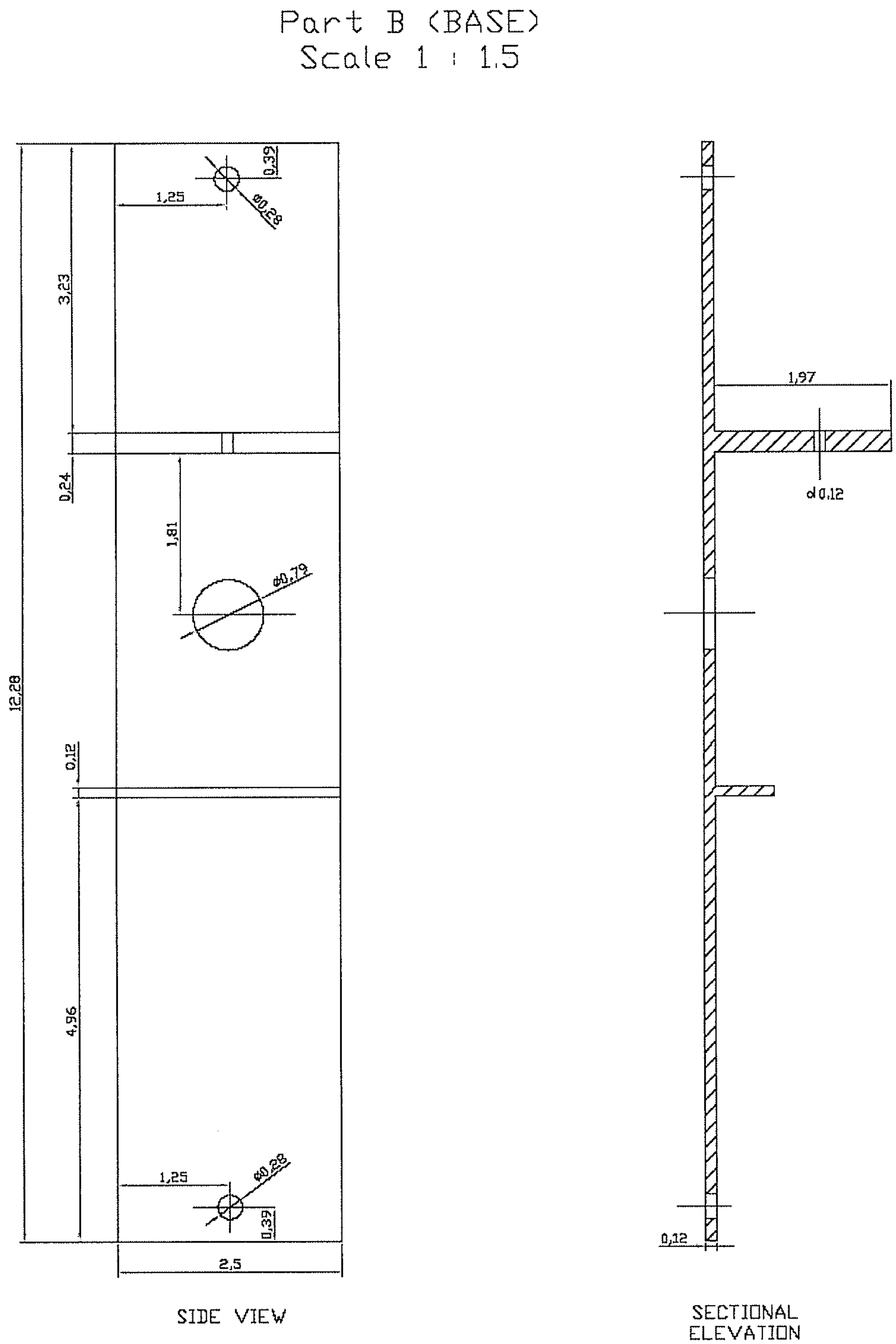

Figure A2: Part B (Base)

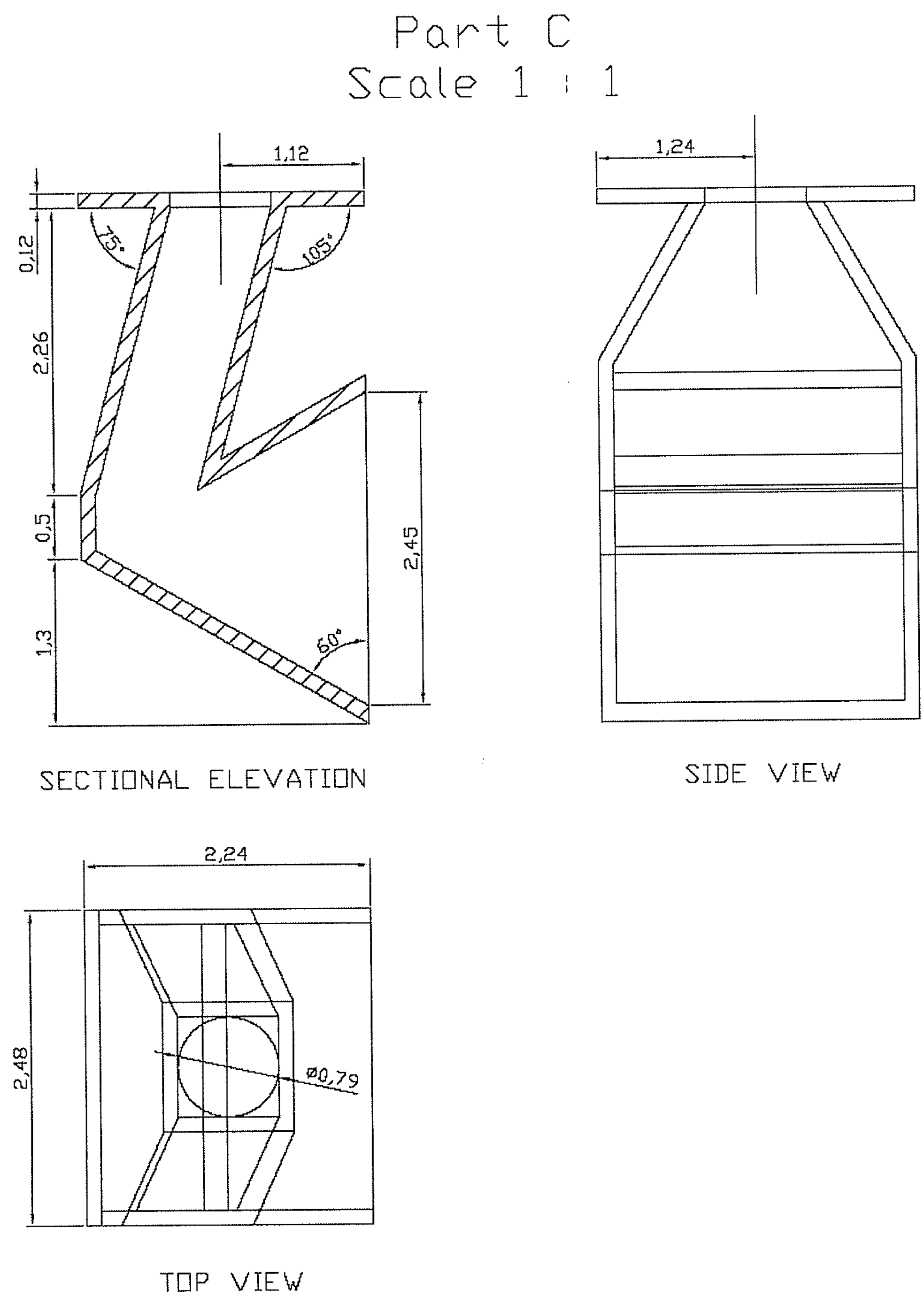

Figure A3: Part C (the Exponential duct)