THE CONTRIBUTIVE BENEFITS THAT STATE-OF-THE-ART SOUND GENERATION TECHNOLOGY PROVIDES FOR ADVANCED TECHNOLOGY SAFETY SYSTEMS IN THE NADS PROGRAM.

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Figure 1. National Advanced Driving Simulator (NADS)

ABSTRACT

The use of synthetic test and research platforms is becoming more prevalent in the effort to capture a better understanding of critical vehicle and traffic safety issues as well as analyze and clarify high probability data. In the area of traffic safety, driving simulators have become the ultimate synthetic human factors research platform. These simulators expand the ability of researchers to explore issues that to date could only be safely studied from raw data interpretation or anecdotal observation and review. As a human factors research platform, realistic driving simulators must mimic and present accurate stimuli to the driver, which influence the dominant or effected human sensory organs. Driving a vehicle presents a "cue hungry" environment. The absence of critical or expected cues influences driver behavior. The importance of providing accurate auditory cues is possibly one of the most subtle, yet critical, and often overlooked prerequisites to achieving realistic immersion in a simulated driving environment. Accurate sound replication includes critical placement of speakers, speaker design, frequency response, appropriate and safe sound pressure levels all leading to creation of a believable, 3-D spatial auditory environment reinforcing the correlated visual and motion cues.

This paper addresses the auditory system criteria, its state-of-art design, philosophy, functional issues, and contributive benefits from the sound subsystem which is incorporated in the NADS program. Additionally, the symphony of properly correlated driving cues is reviewed in relationship with the role of the sound subsystem. Special emphasis is provided on the human factor aspects, which define proper auditory immersion and its expected effect on driver behavior.

INTRODUCTION

Not since the introduction of the Daimler-Benz driving simulator in Berlin, Germany in the mid-1980s has a research platform offered such a comprehensive synthetic-driving environment as the newly commissioned NADS facility in Iowa City, Iowa. Fidelity of subsystem performance replicating real vehicle and environmental behavior was fundamental to the NADS design. The audio environment is one of these critical subsystems because of its hierarchy in human perception and its participation in providing essential cues for vehicle behavior (speed, control, traction, and in after-the-fact recollection when something goes wrong). How often have you heard "what did it sound like" from an engineer or mechanic trying to diagnose a vehicle problem?

The Importance of Audio Cues

Humans are equipped with five senses: sight, sound, touch, taste, and smell. We use these senses in combinations to perform complex tasks. Driving a vehicle involves three of these five, unless you are eating while you are driving. In a driving environment, it is critical for the driver to use sight, sound, and touch to detect and avoid hazards, navigate among other vehicles, and handle the vehicle safely. The complex and demanding nature of typical drivers requires that a driving research platform provide a realistic and believable synthetic environment incorporating all critical cues. One of the most subtle, yet influential of these cues is sound. Because of the sub-conscience nature that sounds contribute to a driving environment, it is often overlooked. Human factor researchers appreciate the challenge that automotive engineers have to alter or correct sound deficiencies in a vehicle design. It was essential for NADS to provide a realistic audio environment that can be altered to evaluate human acceptance and measure response times. Sounds

must be sufficiently real so that results measured in the simulator correlate to real-world data.
A driver's first response to hazards or abnormalities is often an automatic reaction to an audible cue. For instance, the blaring siren of an emergency vehicle can cause us to slow down and look for its source. The unique sound of a rumble strip warns us that we are too close to the edge of the road. The advent of new technology in suspension systems delegates most potholes to being heard rather than felt.

In juxtaposition, the importance of correct sound can be demonstrated by its removal. The lack of sound creates a surrealistic environment. The environment is unrealistic as well as uncomfortable to the driver. The behavior of the driver changes to accommodate for the lack of sensory information. In a research situation this change is devastating to the researcher. The main value of a driving simulator is its ability to provide control and repeatability to experiments. Accurate recreation of actual driving conditions and environments are crucial for an effective outcome. Deviation from actual driving conditions can corrupt the experiment's data. Without correct data the efficacy of the experiment is challenged.

Accurate sound cues enhance motion and visual cues. Even with the advances made in visual and motion technology, a realistic driving environment can not be complete without accurate sound. To our advantage, the brain has an amazing ability to extrapolate. If you provide appropriate visual, motion, and sound cues the mind has a way of "filling in the blanks". The more data you give the brain the easier it is for it to see and react to the environment as if it were real. The visual image of an object seems much more realistic if it is given a sound and a way to interact with the subject. For instance, the visual image of an ambulance coming toward you is more effective if you hear the siren blaring and changing frequency as it approaches, and then displaying an audible Doppler shift as the ambulance speeds by. The more complete the mental picture, the more realistic the reaction to the visual experiences, consequently, the study's results may be more accurate.

Our reality is three-dimensional. A well-developed sound system can also enhance visuals by giving them a position in third dimensional space. Creating 3-D images is complex. Creating a 3-D spatial auditory environment is equally challenging. When an object has a 3-D auditory location, the object itself appears to take on a spatial location. Especially as the object's correlated sound moves with multiple degrees of freedom around the observer, as in the case of the NADS system. Sound directionality, along with proper Doppler shifts, adds realism to visuals.

Criteria for Creating a Three Dimensional Auditory Environment

Understanding the criteria for a three dimensional auditory environment requires that we first explore the methodology behind the audio system of a vehicle. A vehicle creates a rather unique environment for sound generation. To model this environment, the first step is to categorize sounds by location of generation and contributing factors that effect the sound before it reaches the driver's ear. These factors include the reverberation of sounds off the body of the car, and the diffusion of sounds as they pass through the cab walls. These categorized sounds are grouped into three major areas.

> First, sounds created by an external source other than the vehicle.
>
> Second, sounds created by the interaction of vehicle and road surface.
>
> Third, sounds created by the vehicle itself.

Because the last two categories tend to be created, at least in part, by the vehicle they also tend to resonate through the body of the vehicle. The first category entails a sound that is diffused as it propagates through the chassis of the car. These sounds also change in volume and Doppler shift as their position changes with respect to the vehicle.

Keeping these categories in mind and the problems associated with each sound category, we can analyze the criteria for creating a three dimensional sound environment.

There are four areas of importance when designing a three-dimensional auditory environment. With proper design these areas compliment each other in creating a seamless sound field. It is also important to realize the correlation between each area. A problem that may be difficult to fix in one area may be fixed easily in another.

The first area to consider is in speaker placement and design. Speaker placement is important because it is the template for which the rest of the system is designed, and in most simulators is not negotiable because of available space and required point of origination of sound. The second area is in cue recording and/or synthesis. Much of the difficulty in appropriate sound reproduction can be overcome with a properly recorded sound cue. The third area is in the routing and control of each sound cue. This includes mixing and frequency control. The final area is tuning. This is possibly the most difficult, yet critical area.

The ideal speaker location for a well-developed sound field is four speakers located at 90 degrees from each other, with the listener located in the center at equal distances from each speaker. However, because location is a subject of simulator environment, this is not always possible. For instance, the speaker placement of the NADS system was somewhat predetermined by the selection of the simulation environment. The NADS system uses a prefabricated vehicle cab as the foundation for the simulator. This limited the locations available for speaker mounting. Speakers were mounted in locations specified by the automobile manufacturer whenever possible. It was important to keep the speakers non-intrusive to the driver's environment.

A solution to one of the problems mentioned in the sound categories is encountered using speaker placement. The sounds that are created by the vehicle also resonate throughout the vehicle. Placing speakers outside of the cab in places such as the wheel well and motor-mount, and then reproducing those sounds in those locations allow for the natural propagation of the sounds and the resonation of the cab. The NADS simulator incorporated horn speakers in each wheel well and a tactile transducer attached to the motor-mount to reproduce the tire/road interaction and the engine/horn sounds. This was in addition to the interior speaker system.

Speaker design is also important. To determine the speaker design needed, you must determine the frequency response of the sounds to be generated. With the variety of sounds that are possible in a driving situation, frequency responses for individual sounds can range from 60 Hz to 20 kHz. It is difficult to find one speaker that has a dynamic range large enough to incorporate this frequency range, especially with limitations in mounting. The NADS simulator chose to use two speakers instead of one for this purpose, incorporating a woofer with a dynamic range of 60-5000Hz and a tweeter with 5000-20,000Hz.

The NADS simulator incorporated 12 individual sound channels, with four channels being split by frequency and routed to 16 individual speakers. Figure 2. shows a view of speaker locations for all speakers installed in the NADS system.

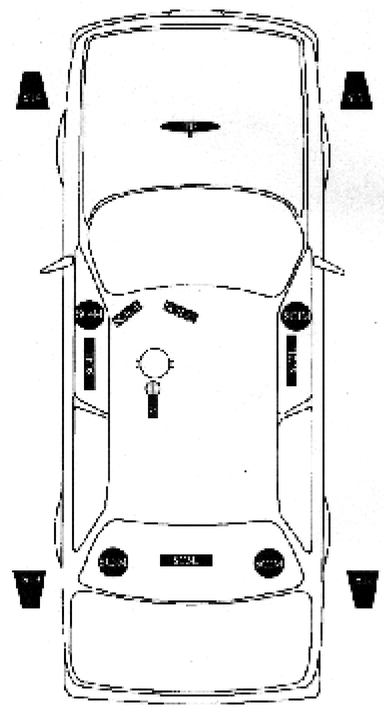

Figure 2. Speaker Configuration of NADS Simulator

Cue recording and/or synthesis is the next area of consideration. It correlates closely with speaker placement. Much of the headaches associated with sound reproduction can be avoided by making certain accommodations when recording sounds. The most obvious, is in recording the sound from the vantage-point of where it will be played. If a sound is played through speakers inside the cab, but occurs outside of the cab you must duplicate this scenario when recording. The same is true for sounds occurring and being played outside the cab. This saves you from implementing complicated transfer functions in software. Recording also must be done with a higher than normal gain to give room for tuning.
With sounds that can't be easily recorded, synthesis is required. For the NADS system most of the sounds that could not be recorded, or could not be singled out of a recording, were located outside of the vehicle. Because the speakers where placed outside the vehicle, again, complex transfer functions were not needed. With these sounds, vehicle dynamics data was collected and matched with frequency responses from sounds collected at the time of the data collection. These responses were used to create a linear graphed description of frequency and amplitude. These linear descriptions were entered into software and used to recreate the sounds using

vehicle dynamics data sent from the NADS central computing system. With a little tuning the differences are imperceptible to the human ear.

Once the sounds are created, they are then routed and controlled. Control is a very important aspect of three-dimensional sound. To give a sound a spatial location, control of each speaker(s) through which the sound plays must be obtained. Also, the amplitude of the sound must be controlled for each speaker. If the sound is associated with the vehicle this is sufficient. However, if the sound is external to the vehicle, the sound must have the ability to traverse between speakers. This is done so that the sound transitions smoothly from speaker to speaker. The NADS system handles the transition of sounds by giving the sound an X and Y coordinate with respect to its own vehicle. The coordinate of the sound is read and the distance from the vehicle is calculated. This calculation determines the overall volume of the sound as

$$1/\ (\text{Distance})^2.$$

At the same time the coordinates are converted into a position in radians. This position controls which speakers the sound is played through and the amplitude for each speaker. Also the sound is shifted in frequency by

$$f' = f\,(1 +/- v/c),$$

depending on if the object is approaching or receding.

Once control of individual sounds is obtained, the sounds must be mixed with a multitude of other sounds needed to create a realistic driving environment. In the NADS system this is done on a speaker-by-speaker basis. Each speaker may play multiple sounds, with multiple amplitude simultaneously.

The final and most important area is tuning. Once the speakers are positioned, sounds are recorded or synthesized and proper control is obtained, adjustments to each area must be made to ensure an accurate three-dimensional auditory environment. The volume of each individual cue must be adjusted to reflect an accurate level for the cue. This level is slightly louder than the actual sound. Because perceptions in a simulation differ from those in an actual environment, subtle cues must be made more dominant.

Individual speakers must have output levels tuned for the variation of speaker distances from the subject. The distances in simulators are not sufficient to justify an output delay, but speakers must have comparable dB levels at the listening point, to ensure smooth transition of sounds from one speaker to another.

An additional consideration is that speaker locations may force an adjustment to output due to their positioning. The ideal speaker placement is rarely practical. In the NADS system, the main speakers were located in the left and right doors and in the rear, against the window. Adjustments had to be made when specifying how a radial position related to speaker output. The range of positions requiring the sound to be played out of the front speakers was greater than that for the back. This was a result of the speakers not being placed at 90 degrees to each other, and the driver was not located in the middle of the sound field.

Benefits of a Three Dimensional Auditory Environment

The set of cues and sources for a driving environment can be very complex. Creating a synthetic representation of that environment requires a significant effort in constructing and correlating all appropriate cues. It always seems to take more effort to duplicate what nature does naturally. An accurately constructed, three-dimensional auditory environment is an important part of a realistic simulation. The complex human sensory system expects a representation of all dominant cues: visual, motion, and sound. If these cues are not matched appropriately, the driver will require adaptation to the simulator environment for the human mind to accept it as real. Accurate sound cueing minimizes the need for adaptation. It also brings depth to two-dimensional visual projections, enhances the realism of motion cues, and adds to the overall sensory cue task loading expected by a normal driver. If a believable simulator experience is successfully created, its correlation to a similar real-world event has greater value. Total immersion of the subject into the driving environment is a major contributing factor in obtaining accurate research data. The quality of the research performed is directly related to the quality of the research platform. NADS has made extraordinary efforts in assuring that it provides a quality synthetic-driving environment incorporating state-of-the-art visuals, motion, and sound.

CONCLUSION

Improved driver acceptance of the simulator environment is the major benefit derived from using a state-of-the-art sound generation system. Creating a three-dimensional auditory environment is a critical part of getting driver acceptance. This can be accomplished with proper speaker design, placement, cue recording and/or synthesis, routing and control, and tuning. The first step in a proper audio design is to study and analyze the environment that is to be modeled. Often this defines what needs to be done or what restrictions are placed on the audio system due to physical or financial limitations. Like a complex cooking recipe, altering the ingredients will alter the outcome. Sound in a simulation is more than what you hear, it is what you believe you hear. The audio subsystem in the NADS system will make a believer out of any driver.

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