Speech Annunciation from Highway Surface Grooves

Charles L. Carnal, Roger A. Kisner, James O. Hylton, William B. Snyder, Jr., and S. Scott Stevens

Abstract—Grooves are embedded in the pavement along the shoulders of many interstate highways in the United States to alert straying drivers with a rumbling sound. Using specially encoded grooves, speech can be annunciated instead.

A groove pattern was devised that resembles a recorded phrase of human speech. The original recording was filtered to remove high frequency noise and then dynamically compressed into an equal amplitude square wave with variable pulse width.

Before committing significant funding to build and test the encoded strip, the phenomenon was empirically modeled using system identification on the sound of an automobile being driven over existing rumble strips. The input was a simple periodic square wave pattern. Then, several phrases from different speakers were encoded into strip signals and used as inputs for the model. A subjective evaluation was performed to determine the most intelligible case.

The selected strip was constructed by milling the groove pattern into sheets of aluminum. Tests with a truck found the fidelity of the sound was intelligible and resembled the simulated sound. An U.S. patent application has been filed.

Index Terms—Rumble Strips, Speech Annunciation, Highway Safety Alerts, Dynamic Compression.

I. Introduction

Accidents occur frequently when tired, sleepy or inattentive drivers fail to keep their vehicles within the proper lane. Almost every driver, on some occasion, has been distracted enough to inadvertently drive off the edge of the road onto the shoulder. Many interstate highways in the United States have grooves embedded in the pavement along the shoulders to warn errant drivers with a loud rumbling sound.

Audible alerts and flashing lights are also found at some railroad crossings, but many lack these costly safety measures. Since accidents involving automobiles and trains are often tragic, it is highly desirable to develop a low cost audible warning system to alert drivers approaching a crossing.

One approach to driver signaling would require an onboard electronic device to detect and decode signals sent by roadside equipment. Legislation to require additional safety equipment for vehicles — although often justified — requires a significant effort and adds to vehicle costs (e.g., air bags, seat belts, and center brake light).

Moreover, safe driving rules and road signs are not effective at preventing some classes of highway accidents. As we know, a moment of inattentiveness, distraction, or drowsiness can lead to an accident or fatality. Other forms of sensory input such as bells at railroad crossings and rumble strips at dangerous intersections are used in special cases to supplement and complement visual symbols.

This study examines the feasibility of creating enhanced rumble strips as a solution to the driver warning problem. Various sounds, including speech, can be encoded in the strips, where vehicle tires rolling over the strips annunciate them. Encoded information could include intuitive warnings to get attention and elicit proper responses similar to the collision avoidance system found in commercial aircraft that annunciate phrases like "Pull Up" to prevent a crash.

As most drivers and passengers have experienced, audible tones can be heard inside a vehicle when traveling on pavement that has a regular pattern of grooves. The sound is generated within the vehicle cab by vibrations in the vehicle's interior imparted by small displacements of the wheels traveling over slots or raised features.

Our results show that grooves or bumps can be designed into road pavement that reproduces short, intelligible messages audible to the driver and passengers. The implementation requires no apparatus in the vehicle. No power source or fragile apparatus is required at a highway location other than the fixed groove or bump pattern in the pavement.

II. Modeling of Acoustic Sources

A. *Mechanics of sound generation by pavement grooves*

Studies of vehicle rolling friction indicate that 1~5 hp (0.746~3.73 W) is dissipated at 60 mph (97 km/h). Of course, power dissipation would vary with vehicle weight, road conditions, temperature, and tire-tread type. We anticipate that the vibrational energy associated with tires rolling over grooves would be similar in magnitude.

One treatment of the mechanics goes as follows: As the tire rolls forward, it falls into the groove. The center of the tire's rotation (and thus the vehicle) drops a small amount, lowering the potential energy. As the tire continues forward

This work was performed at the OAK RIDGE NATIONAL LABORATORY, Oak Ridge, Tennessee, 37831-6285, operated by UT-BATTELLE, LLC for the U.S. DEPARTMENT OF ENERGY under contract DE-AC05-00OR22725.

C. L. Carnal is with Tennessee Technological University and ORNL.
R.A. Kisner, W. B. Snyder and S.S. Stevens are with ORNL.
J.O. Hylton was formerly with ORNL.

and out of the groove, the kinetic energy of forward motion is converted back to potential energy while the center of rotation moves up again. The groove, therefore, converts the energy of forward motion into vertical motion. The same treatment would apply to bumps on the pavement. Figure 1 depicts the tire rolling across a groove.

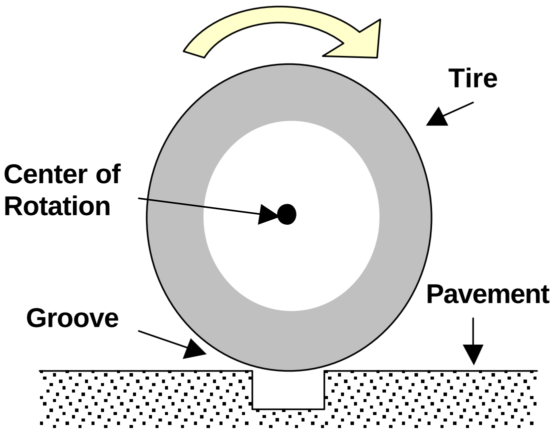

Figure 1. Tire motion over grooved pavement.

A simple model for the tire rolling across pavement grooves gives us a general understanding of the dynamics at work. The vertical displacement of the tire's center of motion due rolling into the groove can be calculated with trigonometry as seen in Fig. 2.

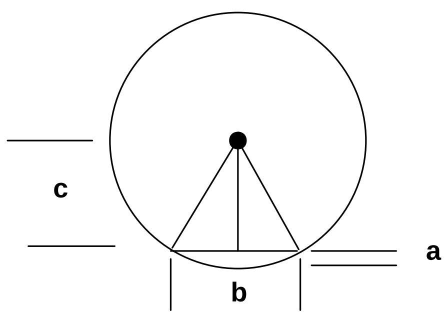

Figure 2. Chord length diagram.

The tire's vertical displacement, a, can be expressed as a function of groove width, b, as follows:

$$a = r - c \tag{1}$$

$$c = \sqrt{r^2 - (\frac{b}{2})^2} \tag{2}$$

$$a = r - \sqrt{r^2 - (\frac{b}{2})^2} \tag{3}$$

A typical tire radius is r = 12 in. (30.48 cm). If we assume a pavement groove width of b = 0.5 in. (1.27 cm), we obtain a small vertical displacement of about 0.0026 in. (0.66 mm). Vertical displacement of the center of rotation is nonlinearly sensitive to groove width according to (3).

The situation is more complex than described by this model. For example, the tire has elastic properties. Various mechanical resonances and vibrations are set up in the tire itself and coupled to the vehicle through the spring, shock absorber, support arms, and other mechanical linkages. Sound also reaches the cab through the air.

The energy to lift a car related to a single pavement groove can be calculated from

$$E_g = \int mgdy = mgy \tag{4}$$

where $g = 9.81\,{}^{m}/_{s^2}$, m is the effective mass, and y is the vertical displacement of the tire's center of motion. For a vehicle weighing 1000 kg, assume that the mass is evenly distributed (i.e., 250 kg per tire). The groove energy per tire becomes

$$E_g = (250\,\text{kg})\left(9.81\,{}^{\text{m}}/_{\text{s}^2}\right)\left(66\times10^{-6}\,\text{m}\right) = 0.16\text{ J} \tag{5}$$

At 60 mph (96.6 km/h) with 0.5 inch (1.27 cm) grooves spaced at 1.0 inch (2.54 cm) intervals, the power required to vertically displace each tire is about 170 watts. A small portion of this substantial mechanical power will be converted into acoustic power in the cab.

B. Empirical Transfer function for automobile acoustics

We recorded the data from a compact automobile driving on an interstate highway at several speeds: 20 mph (32.2 km/h), 40 mph (64.4 km/h), 60 mph (96.6 km/h), and 75 mph (121km/h). Interior sounds were picked up by a dynamic microphone and recorded digitally by a laptop computer. The resulting sound files were analyzed with signal processing software to estimate a model of the system using system identification.

The shoulder of interstate highway was grooved in a regular pattern that generates a distinct audible tone in the cab. The groove pattern had a 4 cm groove width spaced at 23 cm intervals as shown in Fig. 3 below.

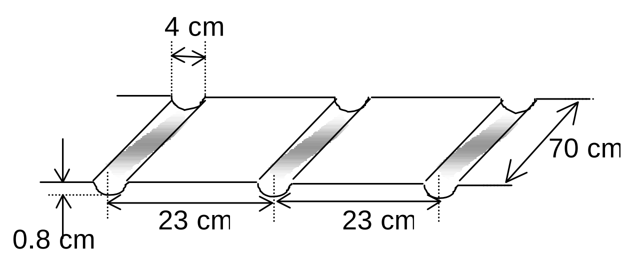

Figure 3. Input Stimulus: Rumble strip groove pattern

This pattern generated a ~117 Hz fundamental at 60 mph. Spectral analysis revealed second and third harmonics. Higher harmonics were masked by the high ambient noise.

A transfer function was developed for the automobile based on comparing the observed road pattern in Fig. 3 with the acoustic signals recorded in the vehicle cab. We used system identification to estimate a linear autoregressive with exogenous input (ARX) model [1], ignoring non-linear phenomena that lead to harmonic generation. After trying several different model orders, a low order model

$$H(z) = \frac{Y(z)}{U(z)} = \frac{b}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{6}$$

yielded an acceptable reproduction of the recorded sound when heard either through headphones or on a loudspeaker. The choice was purely subjective. Fig. 4 below shows a short portion of each output and a synthesized input adapted from Fig. 3. While there appears to be substantial difference between the measured and simulated output, higher order models did not appreciably improve the perceived sound fidelity.

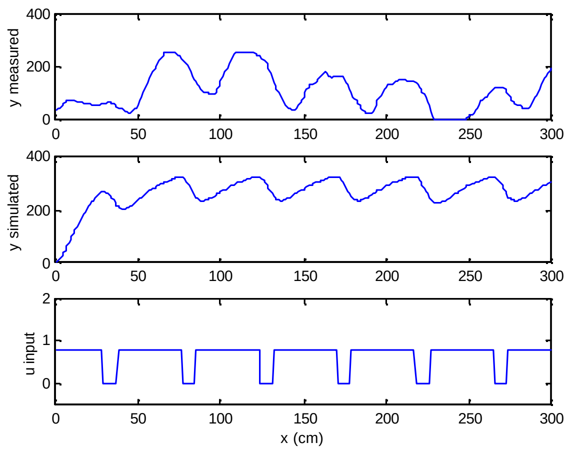

Figure 4. Simulated and Measured Response to Grooves

The estimated transfer function is a two-pole low-pass filter with a 3-dB roll-off at 300 Hz. At 1 kHz, the magnitude of the frequency response is reduced by a factor of ten. This response is shown in Fig. 5.

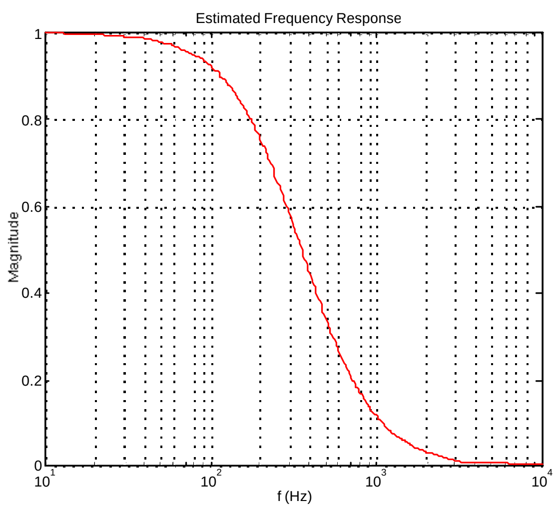

Figure 5. Estimated Vehicle-Groove Frequency Response.

From a single measurement, it is impossible to predict how much the filter response will vary between vehicles. Luxury vehicles would likely exhibit more acoustic attenuation and perhaps lower corner frequencies as compared with sports cars. But, the vehicle's transfer function is useful both in simulating the sounds of a tire running along a section of grooved pavement and for pre-emphasizing a signal that we wish to place as a groove pattern in the pavement.

III. Creation of Road Grooves from Voice Signals

From the analysis conducted, we concluded that it is feasible for a vehicle to "play back" signals more complex than the fixed period (single tone) groove patterns presently cut into pavements. Complex patterns could reproduce either multiple alert tones or a human voice. We envision that it is possible to cut patterns using an analog approach in which every nuance of the sound is captured in the groove patterns. This method would be very similar to the way sound signals are impressed in grooves in vinyl LP records. This approach, however, may not be practical because (1) the patterns that result may contain small features that are easily worn away by traffic and (2) the equipment needed to generate the continuously varying patterns may be expensive.

An alternative approach is to convert the signal into an equal amplitude square wave with varying pulse width. The resulting sequence of fixed depth grooves will require less expensive cutting equipment and be more robust to wear and weather.

To achieve the square groove pattern, we used an extreme form of dynamic compression[1]. First the voice signal is low-pass filtered to reduce noise and reduce the energy bandwidth in anticipation of the limited bandwidth that can be achieved with grooved pavement. Second, the filtered signal is processed by a threshold detector that produces a 0 output value when the input amplitude is above the threshold and a –1 value during the period the signal is below the threshold. The value of the threshold is set just above the ambient noise floor to maximize intelligibility and minimize noise. The extreme dynamic compression method preserves a semblance of the frequency information but severely distorts the amplitude information. When a groove is wide it produces louder sound than a narrow groove since the vehicle tire falls farther down and absorbs more energy when it strikes the far side of the groove edge.

Original signals of the expressions "Pull Left", "Slow Down", "Rail Road", and "Work Zone" were captured from several volunteers using a dynamic microphone and a laptop computer. The individuals had widely varying voice characteristics. Several samples of each phrase were

[1] Dynamic compression in audio applications is the process of decreasing the magnitude of large amplitude signals and increasing the magnitude of small amplitude signals. We commonly hear dynamic compression applied during television commercials to capture our attention—large amounts of compression can make the sound seem louder even though the peak amplitude remains the same. In our application, the dynamic compression is even more extreme since all signal amplitudes become one level.

elicited. We asked each person to vary the inflection and speed upon each rendition. The raw unfiltered phrase, “Work Zone” is shown below in Fig. 6.

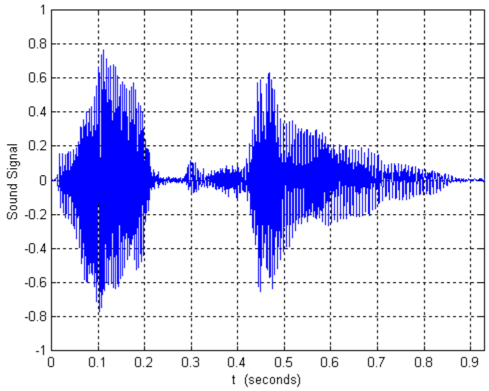

Figure 6. Voice recording of “Work Zone.”

The raw signal was filtered using a second-order low-pass filter with a corner frequency of about 1 kHz to reduce spurious threshold crossings. The filtered signal was dynamically compressed as described above. This flat signal would then become the groove pattern to be cut into the road pavement. Finally, to obtain some confidence that the pavement groove pattern would playback intelligibly in the cab of the automobile, we passed it through the experimentally determined transfer function. This sequence of steps is shown graphically in the signal plots of Fig. 7 below.

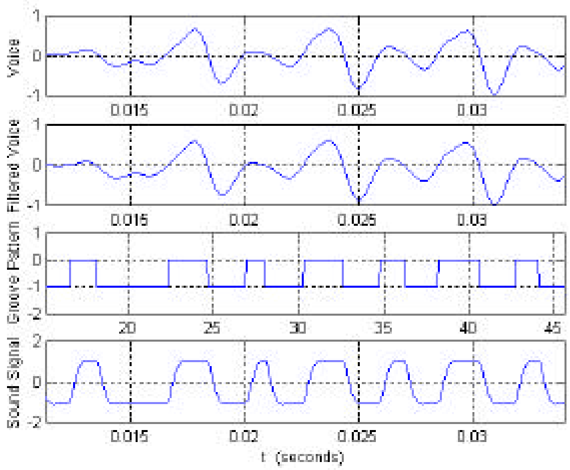

Figure 7. From Raw Signal to Simulated Sound.

Rules will need to be imposed on the groove generation process that places minimums on groove size and limits on spacing. These constraints are needed to prevent overly complex and expensive fabrication and to prevent pavement features that are easily worn down such as a single narrow ridge placed (unsupported) in a wide valley. In most cases, such limits will not adversely affect the sound of the playback. For example, a limit on groove spacing might forbid any groove less than 1 cm in width.

There are other methods that could potentially yield better results based on the observation that the amplitude of the audio signal increases with groove width. This effect results from the tire’s surface contour being much wider than pavement grooves; therefore, unlike a phonograph stylus, the tire does not follow through and touch the bottom of the valleys. Other sound-to-groove conversion methods should be explored in future work. Figure 8 depicts how a segment of pavement grooves would appear to an observer.

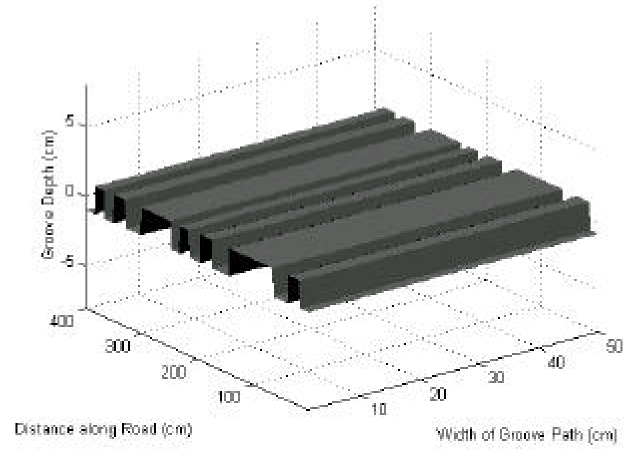

Figure 8. Segment of Pavement Groove Pattern.

IV. Factors Governing Word Choices

The clarity and articulation of the speaker will have a direct impact on the intelligibility of the final pavement-produced message. Production voice-over men and women are regularly used in radio and television announcing. These production voices are chosen for articulation, control, and general mass appeal. Further, their voices are electronically processed with equalization, volume compression, “de-essing,” and other electronic effects to enhance and maximize impact and clarity. Regional dialect is also taken into account for selection of voices in radio and television. Choice of human voice and use of effects should be a part of creating pavement utterance.

A groove pattern is designed for a single vehicle speed. Of course, in practice, the speed will vary from one vehicle to another. In our simulations we discovered that human perception seems to experience a little more intelligibility when speeding up the sound than in slowing playback. There seems to be about ±25 percent speed variation allowed before intelligibility significantly degrades.

For widespread highway alert applications, there will be a need to limit the selection of words and phrases. Some of the selection factors will include word and phrase length, frequency content (fricatives and vowels), and textual ambiguity (dialect and language). It may be that certain words become standardized in pavement playback across a region or the country. We did not attempt to analyze or even catalog a listing of possible words. Word selection and differentiation would be a part of the next phase of work.

After repeated listening tests with the simulation, the most intelligible phrase reproduction was from a female volunteer. Because the frequency response of the system rolls off at a low frequency relative to the bandwidth of human speech, we expected that some high frequency pre-emphasis would improve the intelligibility of the reproduced speech. Apparently the higher pitch of the female's voice serves as a natural pre-emphasis compared to the men in the group.

V. Experimental Results

The groove pattern was milled into aluminum plates at a machine shop. Each plate was 10 ft. (304.8 cm) long, 18 in. (45.72 cm) wide and 1/2 in. (1.27 cm). Eleven plates were placed end-to-end to hold the message "Work Zone." The grooves were 3/16 in. (0.47625 cm) deep. Any grooves less than 0.06 in. (0.1524 cm) wide were not milled to reduce the cost.

A medium-sized truck was driven over the plates, and a video-audio recording was made of the event. The playback sound was similar to the predicted sound from the 2^{nd} order model of equation (6). When the original voice recordings are compared to the experiment recording, one can recognize the original speaker and the particular rendition of "Work Zone" that was used. However, the volume of the phrase was low compared to the sounds of the noisy engine from the vehicle. A vehicle with a quieter engine would have made the sound more intelligible. We discovered this by accelerating to the desired speed and then coasting across the plates with the engine at idle.

VI. Conclusions

Phrases from a human voice can be encoded into pavement grooves that passively playback messages when vehicles drive over them. The limited scope of this study does not predict the limits of intelligibility that may be possible.

The noise level in a vehicle cab interferes with hearing. We expect that drivers in the cabs of large multi-axle vehicles will not be able to hear the message over the sounds generated by their tires. Also the signal echoes generated by several axles in tandem may cause enough reverberation to reduce intelligibility. Still, the possibility exists that some limited number of utterances may be intelligible through the complex transfer function of a large tractor-trailer truck.

If a pattern is cut into the pavement, it cannot be easily changed. Most road signs do not vary their message; however, they can be easily covered or removed if their message is no longer valid.

The cost of designing and manufacturing a machine that can groove pavement with arbitrary patterns has not yet been studied. Long messages may have to be inscribed into pavements to give ample warning of an upcoming change or as a continuous message along the shoulder. However, for economy's sake the longer message may be constructed by concatenation of short repeated messages. Pavement messages take considerable length due to the distance traveled at high speeds. As an example a four-second message at 60 mph requires 352 feet of grooved pavement.
Echo effects from the second vehicle tire may reduce intelligibility slightly. For a typical automobile, we would expect about 0.2 to 0.1 seconds delay from the rear tire (approximately 14 ft. wheel separation at 40 and 70 mph respectively). These effects can be modeled and tested in experimentation in future phases of work.

References

[1] L. Ljung, System Identification: Theory for the User, 2nd Edition. Prentice Hall, Upper Saddle River, NJ. 1999.
[2]
[3]