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3pAA8. Methodology for Physics-Based Sound Composition in Forensic Visualization

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This paper describes a methodology for incorporating physically accurate sound composition in forensic visualizations. The use of sound in forensic visualization provides the viewer a more realistic and comprehensive understanding of actual accident events. Forensic visualization represents complex events such as car crashes, through animation, making it easier to understand the accident. Without sound, however, a visual representation of an accident will lack important information. For instance, sound adds a spatial dimension to animations, defining space through reflection and reverberation. Sound also provides an understanding of important details such as the duration and severity of an accident, and potential sounds heard by a witness. Sound also allows the viewer to experience events in the accident that are occluded from view. Currently, there is no methodology for compositing sound in an animation to follow the principles of sound and reflect the specifics of an accident. Acoustical principals define how sound attenuate, reflects, dampens, blends and changes in pitch and sound level. The unique circumstances of an accident define what sounds are present and the timing and sequencing of these sounds. This paper provides a methodology for creating sound the both follows acoustical principles and reflects the unique circumstances of an accident.

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Methodology for Physics-Based Sound Composition in Forensic Visualization

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1 INTRODUCTION

In accidents involving vehicles, sound can be used in conjunction with an animation to describe important events such as the moment of impact, the duration of the impact, and the severity of the impact. For other types of accidents it may be relevant to verify what a witness could or could not have heard, since sound, like sight, is an important sense through which people understand and interpret events.

Sound also augments the visual interpretation of an event by allowing the viewer to hear the sounds that a witness of the accident would likely have heard. This adds a level of realism and accuracy that an animation without sound lacks. In short, these aspects of sound help organize and clarify the information seen in a forensic visualization through a more realistic and encompassing understanding of the event itself.

Compositing sound into an animation requires a methodology that both adheres to the physical principles of sound and represents the specific events in an accident. Without such a methodology sound may describe erroneous information of the accident sequence or may not adhere to acoustical principles. Sound is rarely recorded or documented at the time of an accident and hence creates a specific problem when trying to accurately represent the sound that would have occurred at the time of the accident. This paper discusses acoustical principles and the equations that define these principles and discusses the implementation of these principles into composited forensic animations. In addition this paper describes a methodology for representing the effect of these characteristics of sound in order to create digitally composited sound in an animation that is both acoustically accurate and incorporates the unique circumstances of an accident. Below is a simple list of the sequence for this methodology:

Methodology	
1	Accident analysis
2	Sound sample collection
3	Compiling & averaging sound samples
4	Sound synchronizing
5	Analysis of the accident environment
6	Application of acoustical principles

The acoustic characteristics and equations and their application in sound compositing as described in the paper apply to far field acoustics only. The reason for this is that camera locations chosen to view animations of reconstructed accidents tend to be in range from, perhaps, as close as thirty feet to as far as several hundred feet or more from the accident event itself. The perceived sound at close range to a sound source can be substantially different than the experience of that sound at a distance and close range acoustics is very sensitive to orientation and surrounding geometry, particularly in the way geometry and orientation affect the sound's frequency spectra. Since animations of accident reconstructions rarely use a close position, the acoustic characteristics at close ranges are ignored.

2 CHARACTERISTICS OF SOUND IN A VEHICLE ACCIDENT

2.1 OVERVIEW OF SOUNDS IN AN ACCIDENT

Many sounds that are present during a vehicle accident have already been individually recorded by movie houses or sound production companies in staged recording sessions. Shattering glass, screeching tires and engine noise have been recorded in isolated environments using hi-end sound recording devices and extensive libraries of these sounds are available commercially. Sound from an actual accident is rarely recorded, but since common accident sounds are already recorded, it would seem simple enough to take pre-recorded sound samples commonly found in an accident, and synchronizing these sounds to an animated reconstruction of the accident.

However, this would prove both inaccurate and misleading; primarily because the environment and specific circumstances of the accident can dramatically change the way those sounds are experienced[12]. For instance, the distance a witness is from the accident changes the perceived sound pressure level. High frequency sounds like horns, or glass breaking will reverberate or echo in tunnels and similar enclosed areas, and the common experience of the Doppler Effect results when sound changes from being a source coming towards the listener to a source moving away from the listener.

As a result of these affects, accurately compositing sound requires three main steps: analysis of the accident sequence, analysis of the accident environment and an application of acoustical principles using equations that define sound behavior. The successful completion of these three steps determines how digital sound samples are composited and modified into a completed sound sequence for an animation. The methodology presented in this paper describes how to adjust pre-recorded sound samples based on an accident analysis and the application of sound defining equations and the proper synchronizing of these sounds to an animated accident reconstruction. The end result is a sound-enabled animation that properly reflects the specific circumstances of the accident and follows the principles of sound behavior.

2.2 FACTORS DETERMINING THE EXPERIENCE OF SOUND

During an accident, many different sounds occur at the same time, yet it is still possible to differentiate between individual sounds. Sound such as shattering glass and tires skidding on pavement are distinguishable because each has unique characteristics such as the waveform, complexity, spectrum, harmonic content, frequency spectra and decibels. Below is a list of some distinct sounds that commonly occur in vehicular accidents:

- Tires skidding and yawing on pavement
- Air underneath vehicle
- Sirens
- Shattering glass
- Tearing of metal and components
- Debris on the roadway
- Running motors
- Equivalent noise (background noise)
- Fluid spills
- Fires

These sounds can be characterized by their decibel levels and frequency spectra. Tables 1 and 2 below show average decibel levels and frequency ranges for some of these sounds[4]. These averages only generalize sound characteristics, and do account for how the experience of these sounds would change due to the unique conditions of an accident. As a result, it is important when compositing sound to consider the specific conditions of an accident that shape the experience of these sounds.

Typical Overall Noise Levels, Expressed in Decibels, Measured at a Given Distance from the Noise Source (Levels below 85dB are weighted)
(L. Doelle, 1965)

Noise Source	Noise level, dB, *re* 0.0002 Microbar
Ticking of watch	20
Quiet garden	30
Average residential neighborhood	43
Light traffic (100')	45
Average traffic (100')	67
Automobile (20')	74
Heavy traffic (25 to 50')	75
Average light truck in city (20')	77
Deisel Truck at 40 mph (50')	85
Inside sedan in city traffic	86
10 hp outboard (50')	88
Boeing 707-120 jet at take-off (3,300')	88
Freeway traffic	85
Inside motor bus	91
Train whistles (500')	92
Average heavy truck (20')	93
Subway train (20')	95
Inside DC-6 airliner	105
Car horn (3')	114
Elevated Train (120')	115
Hydraulic press (3')	129
F84 jet at take-off (80' from tail)	132
50 hp Ambulance siren (100')	138

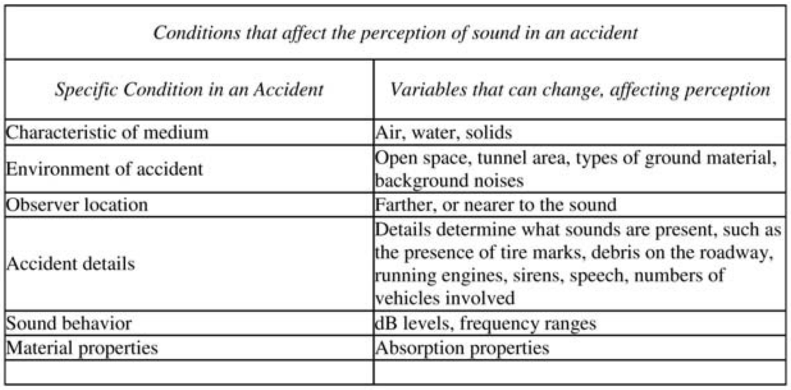
Table 1 – Decibel levels and varying distance

Typical Frequency Ranges for sample sounds of a vehicular accident

Sound Source	Frequency Range (Low 0-500, Middle 500-2,000, High 2,000-20,000
V8 Engine	Low
Large Vehicle Impact	Low
Explosion	Low
Tire Skidding on Gravel	Middle
Hubcap on asphalt	Middle
Tire Skidding on Pavement	Middle
Object through window	High
Shattering Glass	High
Metal Dragging on asphalt	High

Table 2 - Frequency ranges for common sounds in a vehicle accident

Some of the specific conditions that affect the way one would experience sound in an accident can be found in Table 3 below. Sound levels, frequency spectra, echoes, sound attenuation, and Doppler effects are some of the characteristics of sound that change due to unique conditions of an accident. The specific conditions of an accident determine the presence or absence of these sound phenomena, and the degree to which it is experienced. There are also equations that define the attenuation and directivity of sound, the reverberation of sound, the affect different materials have on the absorption of sound, and the relationship between frequency and its sound source. The equations that define acoustical principles are listed below.



Conditions that affect the perception of sound in an accident	
Specific Condition in an Accident	*Variables that can change, affecting perception*
Characteristic of medium	Air, water, solids
Environment of accident	Open space, tunnel area, types of ground material, background noises
Observer location	Farther, or nearer to the sound
Accident details	Details determine what sounds are present, such as the presence of tire marks, debris on the roadway, running engines, sirens, speech, numbers of vehicles involved
Sound behavior	dB levels, frequency ranges
Material properties	Absorption properties

Table 3 - Matrix of specific accident conditions affecting the perception of sound

2.2.1 PITCH CHANGE OF TRAVELING SOURCES

When an object that is producing sound passes by an observer, there is a perceived change in the pitch, since sound waves traveling towards an observer are compressed with a moving sound, and are expanded with a receding sound[1]. This is often referred to as the Doppler Shift and is experienced when ever a vehicle passes a stationery observer. The sounds of the car's tires on the road, or its engine noise have a subtle shift in pitch as it changes from being an approaching sound to a passing sound. This principle is described with the following equations[1]:

$$\text{Approaching sources: } f_{dynamic} = \left(\frac{c_{sound}}{c_{sound} - v_{source}} \right) f_{static} \tag{1a}$$

$$\text{Receding sources: } f_{dynamic} = \left(\frac{c_{sound}}{c_{sound} + v_{source}} \right) f_{static} \tag{1b}$$

-Where c_{sound} is the velocity of sound, v_{source} is the velocity of the sound source, and f_{static} is the frequency of the sound source along the line between the source and the observer. The image below depicts this principle.

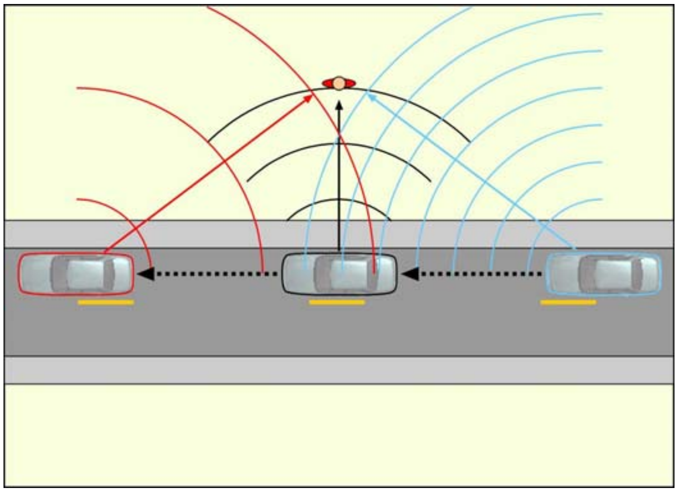


Figure 1 - Image of Doppler Shift

The velocity of sound changes due to temperature, moisture content in the air and many other factors[13], but these factors do not have a noticeable effect on the overall sound sequence being composited and are subsequently ignored in this methodology. For this reason, it is sufficient to define the approximate velocity of sound as[1]:

$$c_{sound} = 1100\, fps \tag{2}$$

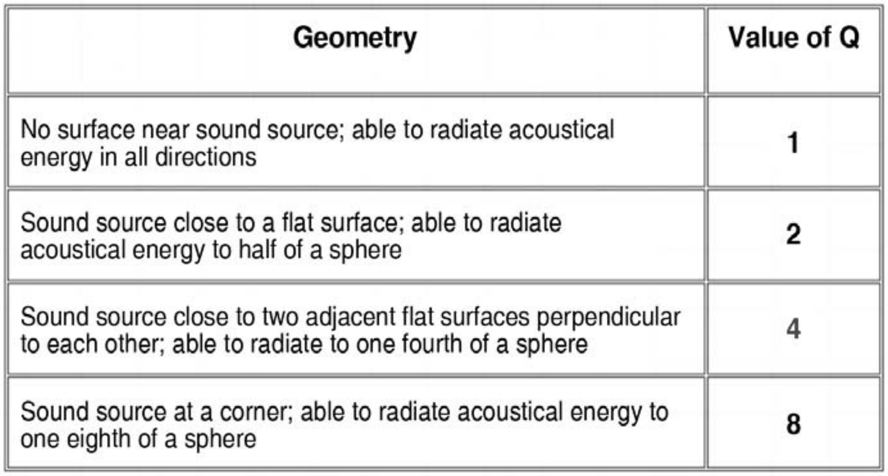
The most relevant application of the equation is for situations where either the camera position or sound source is moving relative to each other. Adjustments to the sound levels would also accompany this equation, since the movement of a constant sound source toward the receiver would be perceived as an increase in sound level.

2.2.2 SOUND PROPAGATION OUTDOORS

Sound level decreases as the distance from the source increases[11]. The decrease in sound level of a sound signal is called attenuation and is due to both the distance from the sound source as well as the angle of orientation relative to the sound source. The angle of orientation relative to the sound source can affect the sound pressure level since sound has directional characteristics. Directivity, as it is known, determines how much sound pressure is directed toward a specific area. As an example, if someone is speaking with there hands cupped over there mouths, the sound will be more “directed” than if they spoke without cupped hands. In a vehicle accident, geometrical conditions of the vehicles and material surrounding sound sources engine noise, will have an effect on the directivity of the sound. This is also coupled with the orientation of the receiver to that sound, as the angle that the receiver is from the sound will have an impact on the perceived sound level. While this effect is more pronounced in a reverberate field, such as indoors or in a tunnel (see section 1.iii.) it is still relevant for open fields as shown in the diagram below. To determine the amount of sound level reduction due to distance and relative angle between two locations each a distance d_1 and d_2 from the source, the following equation is used[6]:

$$A = 20 \cdot \log \left\{ \frac{Q(\phi_A) \cdot d_1}{Q(\phi_B) \cdot d_2} \right\} \tag{3}$$

Where A is the attenuation in sound level as measured in decibels, and $Q(\phi)$ is the directivity of the source. If d_2 is greater than d_1 then the attenuation A is positive, or the sound level is less. Otherwise A is negative and the sound is greater. To assist in determining an estimate for the directivity value $Q(\phi)$, table 4 below list approximate values $Q(\phi)$ given different conditions[3]. Analysis of the accident scenario and the geometrical conditions surrounding the sound sources will provide a guide for which $Q(\phi)$ value to use in the equation.



Geometry	Value of Q
No surface near sound source; able to radiate acoustical energy in all directions	1
Sound source close to a flat surface; able to radiate acoustical energy to half of a sphere	2
Sound source close to two adjacent flat surfaces perpendicular to each other; able to radiate to one fourth of a sphere	4
Sound source at a corner; able to radiate acoustical energy to one eighth of a sphere	8

Table 4 – Values of Directivity Factor

The geometry surrounding the sound source can affect the directivity, forcing more of the sound energy in one direction. Sound as a point source generally radiates, spherically, or in all directions equally, but in collisions and ambient sound, geometrical conditions surrounding the sound source affect its directivity. This occurs when a sound source is surrounded by geometry that act much like walls do with a home speaker system, channeling sound in more narrow directions. This focused sound reaches the receiver with more sound energy than if the sound propagated spherically. This additional energy needs to be accounted for in the $Q(\phi)$ value. If the sound source does not have directivity, then a value of 1 can be used. For a $Q(\phi)$ other than 1, two conditions must exist. First, analysis of the sound source geometry must be determined to affect the directivity of the sound, and second, the receiver must be within the projected angles of the directed sound. For instance, if a sound source is determined to have geometry affecting directivity such that a value of 2 is determined (a hemispherical projected sound pattern) then only the receiver position that lay within the hemispherical projection should calculate the $Q(\phi)$ value of 2. Receiver positions behind the hemispherical directivity projection would not use this value, but rather the default value of 1. The image below depicts the principle of attenuation and directivity.

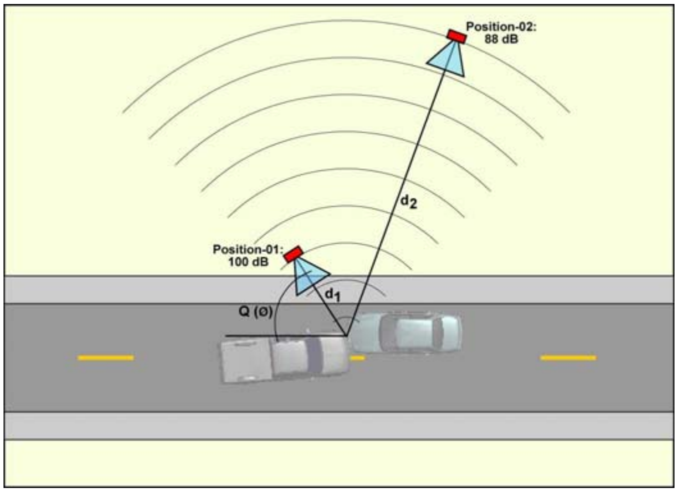


Figure 2 -Image of Attenuation and Directivity

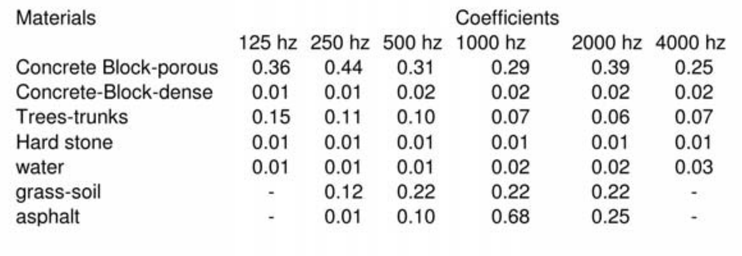
When applying this equation, the sound level a given distance from the source (d_1) is usually known and the attenuation of the sound level at a different distance (d_2) is desired in order to calculate the sound level at that location. A suitable application would occur when a camera view cuts to another view. Since the sound level is established in one view, the change of camera location will have an affect on the perceived loudness of the sound. For instance, if a camera is located 50 feet from a sound source of 100 dB, and then switches to a view 200 feet from the sound source, there would be a relative decrease of approximately 12 dB, assuming a $Q(\phi)$=1.

2.2.3 SOUND ATTENUATION IN ENCLOSURES

Outdoors, sound ceases when the source stops, provided that there are no objects off of which it can reflect. In an enclosed or covered area, however, sound energy lingers and this decay is called reverberation[11]. For traffic accidents, this enclosure would likely take the form of a tunnel or underpass, or even a parking structure. The reverberation time (RT) is defined as the length of time, in seconds, it takes for sound to decay by 60 dB. Reverberation time is directly proportional to the volume of a space and inversely proportional to the units of absorption, or sabins, as expressed in the equation[11]:

$$RT = \frac{KV}{a} \tag{4}$$

In which RT = reverberation time in seconds. K=.161(for volumes in m^3) V= volume in m^3 and a=total absorption in sabins. Sound absorption is measured in sabins and different materials absorb sound energy more at some frequencies than others. This makes it important to determine the sound absorption for materials and varying frequencies. Table 5 is a chart of various absorption coefficients at varying frequencies.



Materials				Coefficients		
	125 hz	250 hz	500 hz	1000 hz	2000 hz	4000 hz
Concrete Block-porous	0.36	0.44	0.31	0.29	0.39	0.25
Concrete-Block-dense	0.01	0.01	0.02	0.02	0.02	0.02
Trees-trunks	0.15	0.11	0.10	0.07	0.06	0.07
Hard stone	0.01	0.01	0.01	0.01	0.01	0.01
water	0.01	0.01	0.01	0.02	0.02	0.03
grass-soil	-	0.12	0.22	0.22	0.22	-
asphalt	-	0.01	0.10	0.68	0.25	-

Table 5 - Common Coefficients for Roadway material

This information can be used when determining the value for *a* in the equation above. The equation to determine total sabins is[11]:

$$a = S\alpha \tag{5}$$

Where S is the surface are in sq feet and α is the average coefficient of absorption. It is important to note that the materials generally found in and around accident sites tend to have little absorption affect on the higher frequency ranges – above 1000 Hz[13]. This means that the experienced reverberation of sound in an enclosed space such as a tunnel or heavily wooded roadway would be for the higher frequencies only, the lower frequencies being absorbed or attenuated more rapidly.

2.2.4 ECHOES RESULTING FROM TRANSIENT SOUND

Including echoes adds a level of realism to an animation. Echoes occur from transient sound sources in enclosed or covered areas. Echoes are reflected sound waves that are far enough apart in time that they are distinguishable from the original sound source[15]. A transient sound wave is a short term effect, as compared to the steady state propagation of sound. This difference makes transient sound generate a distinguishable echo, where a steady state sound would cause reverberation as described in section iii. To determine if an echo exists, simple time and distance calculations can be used.

$$T_{echo} = \frac{d_{reflected-surface}}{c_{sound}} \tag{6}$$

Where T_{echo} is the length of time before the sound is heard again, d is the distance from the receiver to the surface off of which sound is reflecting, and c_{sound} is the velocity of sound in air. If the echo time is greater than 50 milliseconds, it is likely that an echo would be perceived[14]. Echo times less than 50 milliseconds would contribute to reverberation, and overall sound levels, but would be imperceptible as a distinct sound. Calculations for distance should be made from the receiver to the most perpendicular reflecting surface along a straight line. This simplifies the process, though sound in an enclosed environment would naturally propagate spherically.

2.2.5 DELAYS BETWEEN VISUAL EVENTS AND PERCEVIED SOUND

There may be a situation where a camera location in an animation may be several hundred feet from the accident itself. This distance can cause a delay between when the sound is created in the accident and when it would be perceived at the camera location. The effect this has in the animation is that the event of that produces the sound will occur visually, before the generated sound reaches the observer. This delay can add realism to the animation, since it properly represents a delay on would hear at that same camera location. This delay can be accounted for by using the same time and distance equation for echoes.

$$T_{delay} = \frac{d}{c_{sound}} \tag{7}$$

Where T_{delay} is the amount of delay before the sound source would be heard at the given camera location. Sound travel at a very fast rate, so short distances would not have a perceptible delay. For longer distances, over 100 feet, however, a delay will be noticeable. For example, if an observer is 250 feet from the sound source, there would be a noticeable delay of almost a quarter second.

2.2.6 AMBIENT SOUND LEVELS: EQUIVALENT SOUND LEVELS (LEQ)

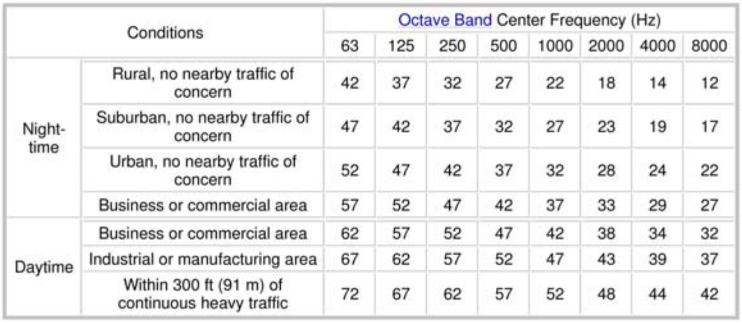
The equivalent noise level, or LEQ, is the average sound level of ambient or background noise[14]. Tire motion on pavement at high speeds, engine noise, and the flow of air around vehicles create such sound. The sound created by traffic normally resides in the range of 50 to 95 dB[9]. Incorporating LEQ in the sound sequence is important since accidents often happen in highway areas and highway noise would be noticeable to an observer. Adding background sound in an animation (particularly highway accidents) is important for realism, but obtaining an actual sound sample from the accident site, while preferred, is not always practical. For this reason, it is possible to determine the average sound level for background sound in a specific highway setting through calculations that reflect the number and size of cars that pass. This provides an average sound level. Since the sound is generated by known source (tire on pavement, engine, and vehicles passing through air) and since recordings of these sounds exist in digital sound libraries, it is reasonable to “recreate” background sound through composition of this pre-recorded sound clips. The relative sound level of this composition is set by the calculations for the expected Leq level in that area. The recorded sound source could even be used in the animation composite. If the actual ambient sound can not be recorded or measured the following equation can be used to determine a suitable starting level[9]:

$$LEQ_{average} = 41.2 + 10\log(q) \tag{8}$$

Where q is the total number of vehicles per hour. Since sound levels from traffic on highways and roadways differ, a correction (C) equation can be used to get a more accurate LEQ. The solution to this equation should be added to the equation for a total average LEQ[9].

$$C = 33 \cdot \log\left(v + 40 + \frac{500}{v} \right) + 10 \cdot \log\left(v + 40 + \frac{5p}{v} \right) - 68.8 \tag{9}$$

Where v is the average speed and p is the percentage of heavy vehicles (0-100%). An easier alternative, though, is to use a graphical chart that has average dB levels based on the type of roadways. Table 6 below lists average noise levels at varying frequencies for different roadway[5].



Conditions		Octave Band Center Frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
Night-time	Rural, no nearby traffic of concern	42	37	32	27	22	18	14	12
	Suburban, no nearby traffic of concern	47	42	37	32	27	23	19	17
	Urban, no nearby traffic of concern	52	47	42	37	32	28	24	22
	Business or commercial area	57	52	47	42	37	33	29	27
Daytime	Business or commercial area	62	57	52	47	42	38	34	32
	Industrial or manufacturing area	67	62	57	52	47	43	39	37
	Within 300 ft (91 m) of continuous heavy traffic	72	67	62	57	52	48	44	42

Table 6 - Average sound levels (in dB) for various traffic speeds

To determine an appropriate LEQ, determine what type of roadway the accident occurred on, and average the levels. The bulk of traffic noise, particularly on highways, will come from tire noise, which will occur in frequency ranges from 250-2000 Hz. Since this is simply background noise for the sound sequence, the accuracy of the ambient levels at every frequency is not as important as the accuracy for the audible sounds from the accident itself. It is, however, relevant to have a reasonable starting dB level to work with when compiling the specific sounds of the accident.

Whenever possible, however, it is preferable to record an actual a sound sample from the area of the accident, along with recorded dB levels, around the same time of day as the accident occurred, since travel patterns vary greatly throughout the day. This provides the most realistic background sound for an animation.

2.2.7 ADDING SOUND SOURCES

In the event that two sound sources emit sound simultaneously, an equation can be used to determine the overall increase in perceived sound level. If, for instance, additional siren sounds occurred, or an addition tire screeching event occurred simultaneous with other sound events, the addition sound sources would increase the sound level, but only marginally. The following formula determines the total sound pressure when combining sound sources[1].

$$Lp_{total} = 10 \cdot \log\left(10^{\frac{Lp_1}{10}} + 10^{\frac{Lp_2}{10}}\right) \tag{10}$$

Where Lp_1 and Lp_2 are sound levels being combined. For instance, the addition of two sound sources of equal sound level would have an increase in total sound dB level of 3 dB. This rule of thumb will help make easy adjustments to the sound sequence in the event additional sound sources are added.

3 COMPOSITING METHODOLOGY

The following steps outline a methodology for compositing sound into an animation:

1) **Accident Analysis:** Analyze the accident and determine what sound sources are present.

2) **Sound Sample Collection**: Obtain these sound sources individually as digital sound clips.

3) **Compiling and Averaging Sound Samples**: Compile the sound clips and adjust the dB ranges such that each source is distinguishable.

4) **Sound Synchronizing:** Synchronizing the sound sources to match the corresponding sound event in the animation.

5) **Analysis of the Accident Environment:** Analyze the environmental conditions and location and movement of the sound sources and sound receivers (witness and cameras).

6) **Application of Acoustical Principles:** Determine which equations of sound behavior are relevant to the accident and adjust the compiled sound files according to these equations.

3.1 ACCIDENT ANALYSIS AND SOUND SAMPLE COLLECTION

An analysis of the accident details yields information such as the sequence of events, the types of component interaction that occurred, and the presence of sound producing events such pavement gouging, shattering glass, or tire marks on the roadway. Below is a limited list of information that might be obtained. Accident details would come from the accident reconstruction itself, since the sound composite would most likely accompany an animation created from the accident reconstruction. Other relevant information may be obtained through analysis witness statements, photographs, and analysis of other scene and vehicle issues that are not part of the reconstruction.

Accident details to be analyzed:
- Number of vehicles involved
- Types and numbers of collisions
- The vehicle characteristics
- Vehicle Speeds
- Background noise
- Braking events
- Rim and roadway gouging events
- Vehicle interaction with road objects & structures
- Collision details (what components are involved, debris)
- Direction of travel and distances to POI
- Post collision details such as fire or fluid spills

These details describe what sound sources would be present during the accident sequence. The sound sources, then, would be collected as individual sound samples. Many of these sounds have been prerecorded individually and are commercially available in digital sound libraries. These libraries often include several variations of the same sound type.

For instance, an extensive sound library would have tire skidding sounds from a passenger vehicle at 30 mph, 40mph and 50 mph. The library might also have these same speeds and skids for a tractor-trailer or large van. This wide variety of sound samples makes it easier to match the digital sound samples to the potential sound source determined to be present at the accident. In short, each sound source that is identified as being present in the accident is collected as an individual digital sound clip.

As an example, if an accident involves a van rollover, in a city highway, with pre-roll tire marks, broken side windows and a pole impact, then the list of sounds to be compiled would include, engine noise, tire skidding, impact of metal on ground, glass breaking, tearing metal, air turbulence, and background noise. It is likely that there are several versions of each of these sounds, and offer better options for choosing the sound closest to the description details.

3.2 COMPILING AND AVERAGING SOUND SAMPLES

There are enormous differences in the way that sound sources are recorded. The sensitivity of the recording equipment, the quality of the sound source, and the placement of the microphones all vary, and these produce significant differences in the raw digital sound clip[12]. For this reason adjusting characteristics of the sound samples when compiling them creates a more consistent thread of sound quality between the individual sound clips. These adjustments would include normalizing the sound samples and adjusting the loudness (dB levels) until the sound compilation as a whole represents a consistent sound event with distinguishable individual sound sources. To develop a standard for creating a consistent sound event, two techniques are used as guidelines for adjusting and compiling individual sound samples into one sound sequence.

The first technique addresses the difference in spectral balance in outdoor sounds for high and low frequency sound waves. Close range and distant sound differ in the relative amounts of direct and reflected sounds, and this in turn colors the way one hears high and low frequencies. Outdoors, air absorbs high frequency tones more than lower frequency tones[8]. The absorption of sound pressure level due to this attenuation is shown in Figure 1.

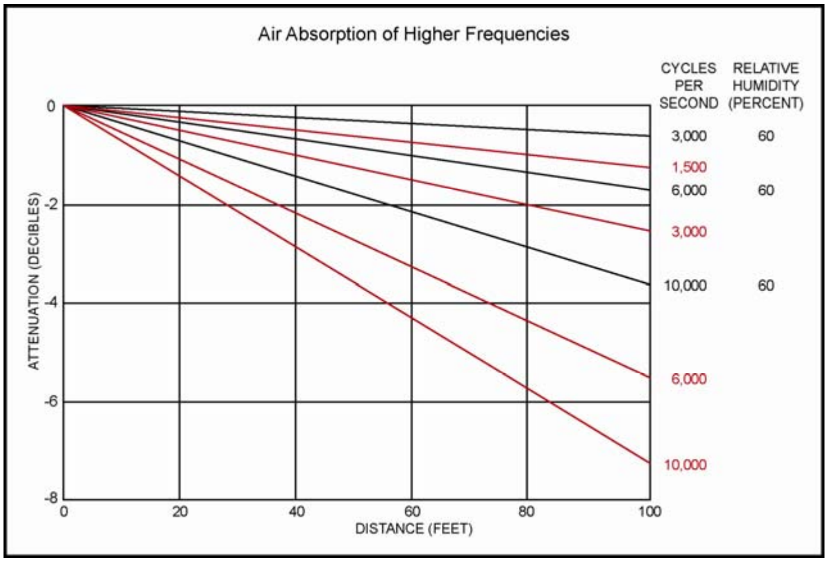


Figure 3- Air absorption of higher frequencies

This real world phenomenon makes composition of prerecorded sounds particularly important. Pre recorded sounds are typically close microphone conditions, and often in enclosed and contained environments. The sound of a horn, for instance, when recorded with a microphone close to the sound source, has a very different sound spectrum that that same horn recorded outside, since the high frequency tones will be more prominent in this condition that in real life where the sound source is farther from a receiver. This is due to the reflection of the sound source as it approaches the microphone as well as the absorption of higher frequency tones in the air as it travels this distance. In short, prerecorded sounds of higher frequency sound sources should be composited to reflect the real world phenomenon of high frequency absorption through air.

Not only does the medium through which sound travels, typically air, affect the spectral balance of high and low frequency, but the human ear itself experience frequencies through various weighting. In other words, the human ear is more sensitive to certain frequencies, resulting in a perceived loudness of one frequency over another, even if the actual dB levels of the two frequencies are the same. For instance, the human ear is most sensitive in the 500 Hz to 6000 Hz range and least sensitive at extremely high and low frequencies outside this range. The Fletcher-Munson graph in Figure 2 represents pressure levels of pure tones that are considered equal in loudness and respective frequencies.

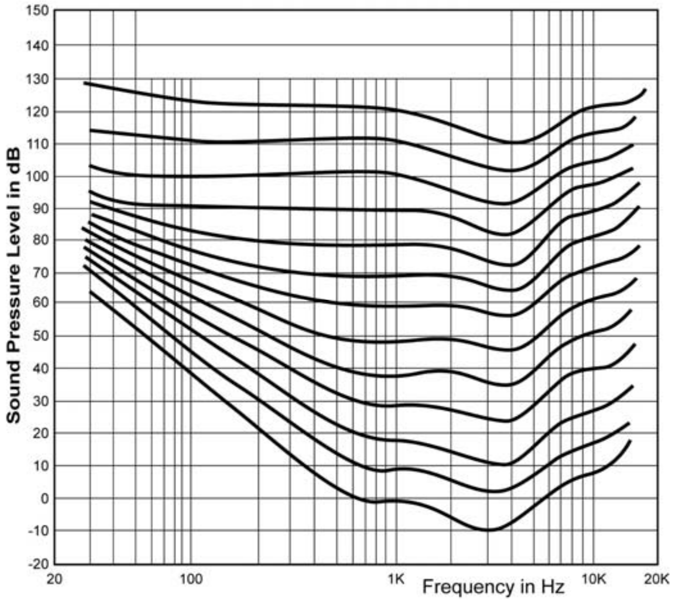


Figure 4- Fletcher-Munson Graph

For instance if a 1kHz tone is heard at 60 dB, a tone at 100 Hz would have to be heard at 73 dB to be perceived as equally loud. While this characteristic of the human ear is important to understand how people experience sound, actual recorded and composited sound sources should not be modified according to this chart, since the human ear performs this function automatically.

The second technique provides a guideline for sound sample adjustments based on frequency level distribution and decibel level patterns that have emerged as a result of analysis of sound in real vehicular accidents. This analysis helps form a common pattern of a sound event in a vehicular accident. This pattern is used as another criterion for physic-based sound composition.

The first pattern is the relative change in dB levels due to impacts. At impact, there is typically a large increase in the measured dB levels as the vehicles come into contact. Figure 3 shows a sample waveform, highlighting where the dB levels change coincides with an actual vehicle impact. Wave forms of sound samples from several real vehicle crashes were analyzed, measuring the dB change from pre impact to post impact over an average time of 2 seconds.

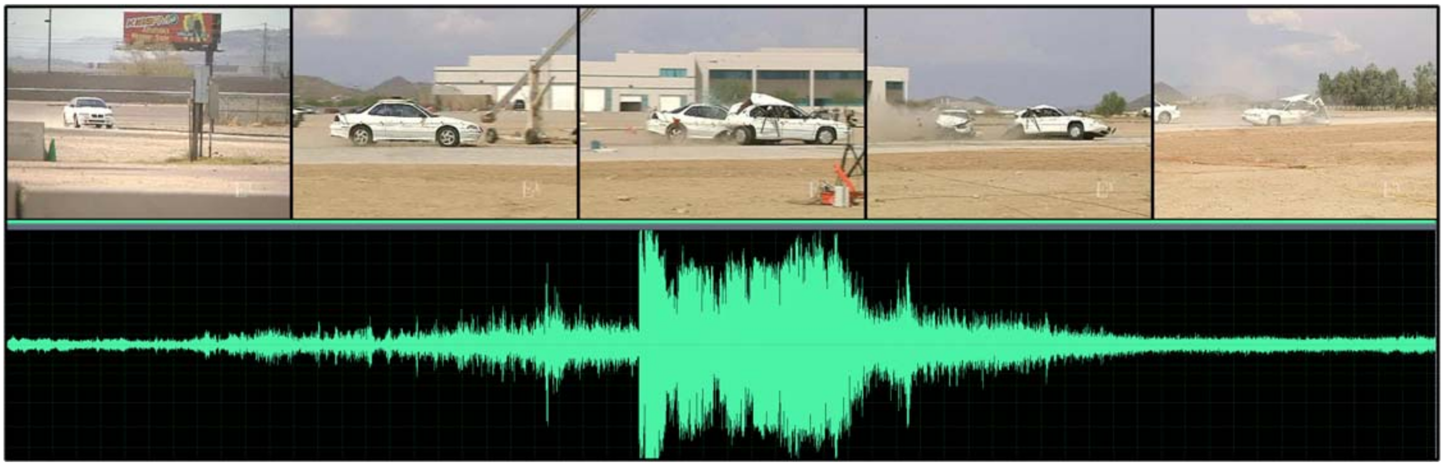


Figure 5 - Waveform showing increase in sound level at impact

The results of the analysis, as shown in Figure 4, demonstrate an average gain of 10 dB between pre-impact and post-impact. This would correlate to a sound level gain at impact of ten times that of the sound pre impact. In experimental tests, though, it was found that an increase in 10dB is perceived as only doubling the loudness[17].

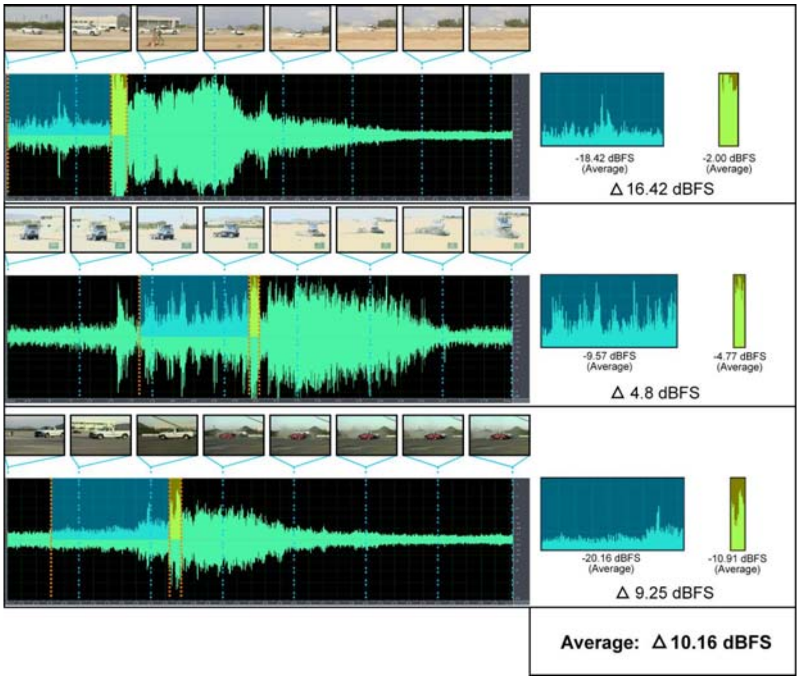


Figure 6 - Waveform showing average increase in sound level between pre impact and post impact

The second pattern is the relative distribution of frequencies in a vehicle collision. Vehicle accidents, while unique, contain similar sound sources that when combined create a general sound pattern of a vehicular accident. Tearing of metal, shattering of glass, and sound pressure from the impact are common sounds in an accident that have their own unique pattern of frequencies and when combined into one sound event, as in a vehicle collision, the sounds merge to form a single source that also has a distinct pattern of frequency spectra. Analyzed individually, isolated and prerecorded sound sources show patterns of frequency spectra. Engine noise tends to produce most of its sound in the lower frequencies while metal on asphalt and fluid hissing sounds tend to produce the majority of their sound in the higher frequencies. Figure 5 shows several pre-recorded sound sources and the frequency ranges that the sound is produced in.

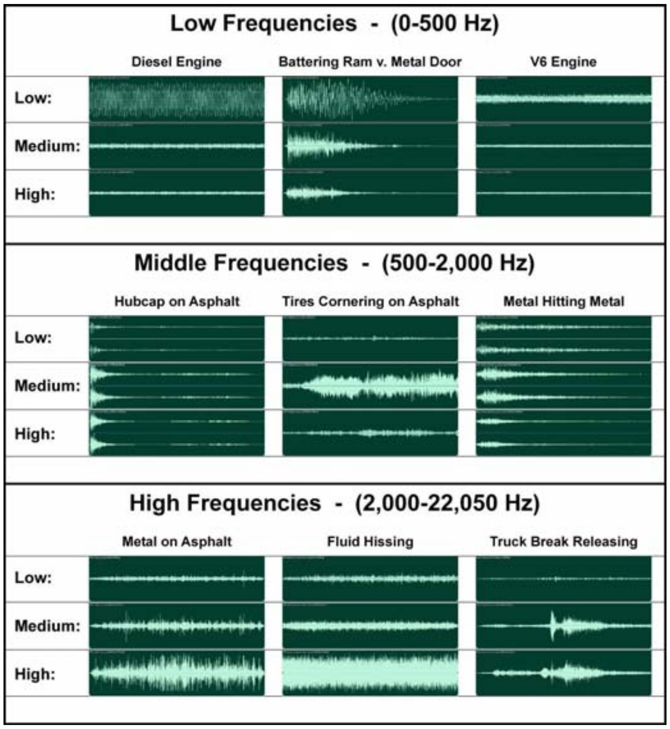


Figure 7 - Frequencies ranges of common vehicle accident sounds

When these sounds are composited in to a completed sound sequence, there is also a pattern of frequency distribution that suggests a fingerprint for sound frequencies in car crashes. To analyze what this fingerprint might look like, several crash test sound clips were analyzed according to the decibel levels present at varying frequencies. Figure 6 shows three sound clips from real world crash tests that are broken down into three frequency ranges; low middle and high.

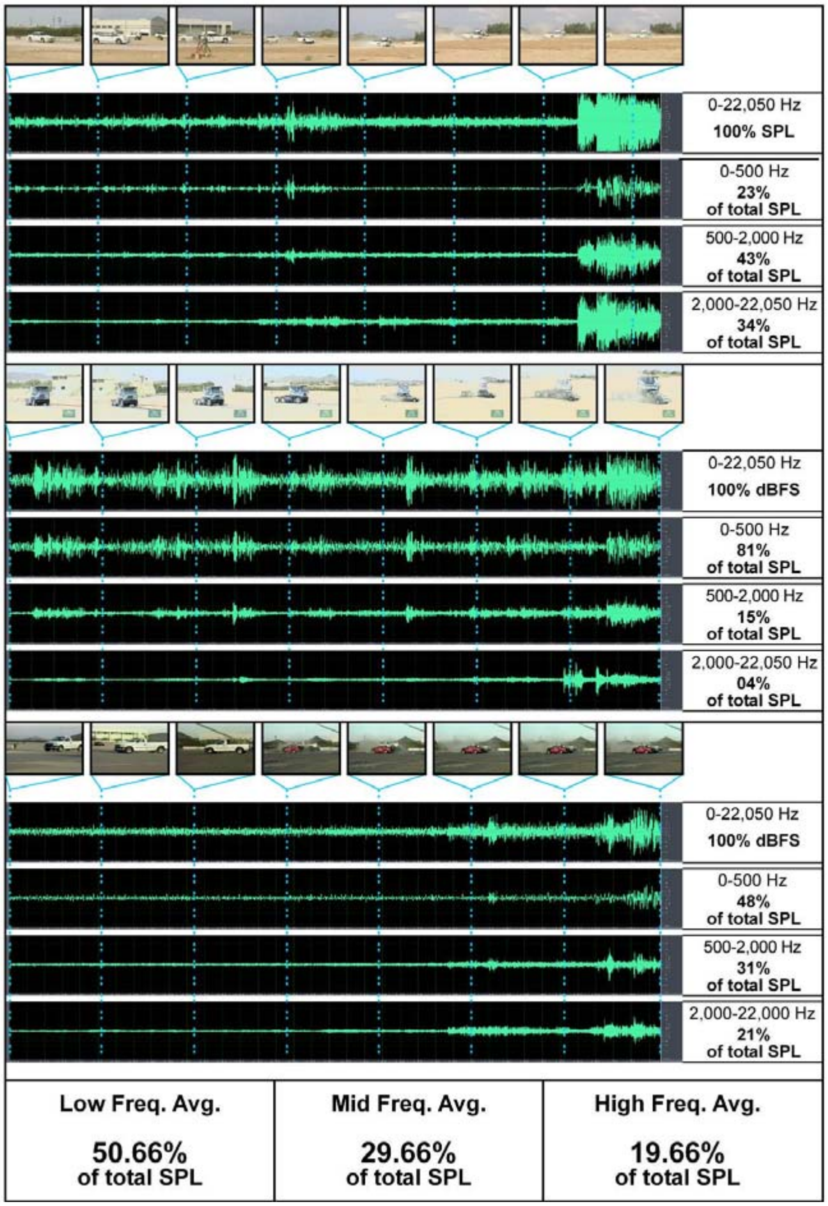


Figure 8 - Waveforms showing distribution of frequency ranges in total sound source

These frequency ranges are 0-500 Hz, 500-2000 Hz, and 2,000-22,050 Hz respectively. This breakdown is based on the human ear's capability of hearing frequencies from approximately 20 to 22,000 Hz. Averaging the distribution of frequency ranges in all three sound sources creates a signature for sound in an accident. This pattern shows an average distribution for low middle and high frequencies distributed as 51%, 30%, and 19% respectively. This suggests that the majority of the total sound energy from a vehicle accident resides in the lowest third of audible frequencies.

3.3 SOUND SYNCHRONIZING

Synchronizing sound to an animation is a relatively simple part of the methodology. After analyzing the accident, the general sequence of events will describe when particular sound events occur. The sound of tire screeching on pavement would logically occur when tire marks are being deposited on the roadway in the animation. As a general rule, sound sources such as the tearing metal, glass breaking, hissing of liquid on engines need to occur at the same time these events occur visually in the animation. Adjustments to the sound such as delay due to the distance the observer is from the sound, or echoing due to the environment conditions, come later in the process, when equations are used to determine how these sound qualities need to be changed.

3.4 ANALYSIS OF ACCIDENT ENVIRONMENT

An analysis of the environmental conditions surrounding the accident is necessary to determine which equations to use to modify sound samples digitally. For instance, if the accident occurred in a tunnel, there would be reverberation from higher frequencies. This would require a calculation for determining the length of echoing time given the volume of space. The result of this calculation would be used to modify the sound sample digitally so that the adjusted sound echoed a corresponding length of time. As another example, if multiple vehicles were involved in the accident, the presence of these additional sound sources would contribute to the overall sound level. The addition of these sound sources would raise the perceived sound level according to the equation for adding sound sources. The result of this equation would determine how much the sound should be amplified digitally. Below is a list of the environment conditions that should be analyzed and represented in compositing sound.

Presence of enclosed areas in the accident site
Distance of cameras relative to sound source
Movement of camera relative to sound sources
Background noise (LEQ)
Weather conditions
Location of obstructions between observer and source

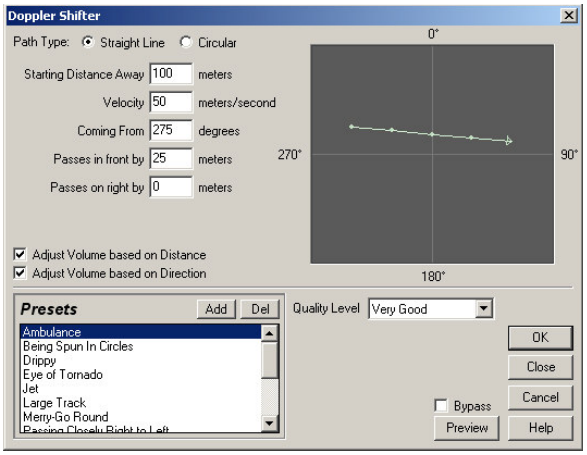
All of these factors can dramatically alter the experience of sound. Once identified, appropriate equations can be used that determine how any part of the sound sequence should be modified to properly reflect the physical principles of sound.

3.5 APPLICATION OF ACOUSTICAL PRINCIPLES

Sound editing software is commercially available. Some common sound editing software packages include Audition, Cakewalk, Sound Forge, and Wavelab Studio. Sound editing software can analyze sound at high sample rates, and wide ranges of sound level and frequency. Below is a table of the different characteristics that sound-editing software can analyze and adjust.

Characteristic	Possible adjustment
Frequency Levels	Raised or lowered
Sound levels	Louder or softer
Reverberation	Extended or shortened
Delay	Adjusted timing
LEQ (ambient noise)	Added background sounds
Frequency tones	Cancelled or inverted

A sound sample can have some or all of the above characteristics adjusted to reflect the specific conditions of an accident. After determining the relevant details of the accident sequence and the specific environmental conditions that affect the way sound is perceived, the equations described in Section 1 can be used to adjust the compiled sound sequence such that it adheres to the principles of sound physics. Some sound engineering software can adjust a sound sample in multiple ways at once, making the process easier. Adobe Audition 1.5, for instance, has a controller for creating the effect of pitch change due to a passing sound source that adjust the change in decibel level at the same time. This makes the process easier since separate calculations would not need to be done for both the change in pitch and the change in dB level for an approaching and receding source. The image below demonstrates an easy to use interface for adjusting pitch and decibel levels for a moving sound source. Adobe Audition 1.5 appropriately calls this controller the "Doppler Shifter".



Path Type: ● Straight Line ○ Circular
Starting Distance Away 100 meters
Velocity 50 meters/second
Coming From 275 degrees
Passes in front by 25 meters
Passes on right by 0 meters
☑ Adjust Volume based on Distance
☑ Adjust Volume based on Direction
Quality Level Very Good
☐ Bypass

Figure 9 -Image of Adobe Audition's "Doppler Shifter"

4 CASE SAMPLE OF COMPOSITE IN AN ANIMATION

4.1 OVERVIEW OF THE ACCIDENT

To demonstrate the use of this methodology, a case sample is shown here through waveforms and images. Unfortunately it is difficult to communicate sound in a paper. However, to the degree possible, the adjustments to sound samples and the resulting composited sound sequence is represent through visual means to illustrate the principles in this methodology. The accident depicted in the animation in Figure 7 is a multiple vehicle accident, involving several tractor trailer, a large pickup truck, a passenger car, a SUV and a van.

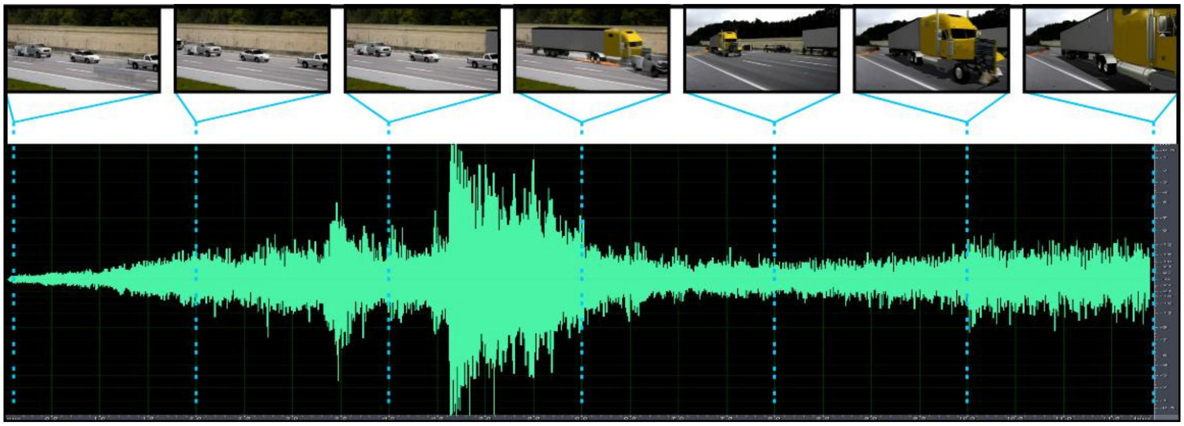


Figure 10 – Multi-vehicle animation

The accident sequence depicted above began when a tractor-trailer swerved to the left of a line of stopped vehicles on a major highway, in an effort to avoid hitting them. The tractor-trailer behind, however, was unable to avoid impacting the stopped vehicles and subsequently drove the pickup truck into the vehicles lined up ahead of it. The pickup truck was pushed to rest across the highway into the rough grassy shoulder and the other vehicles that were stopped, come to rest in the travel lanes of the highway. The first tractor trailer and the SUV engaged to the right of the main collision ended up in the left shoulder.

4.2 RECONSTRUCTION OF THE ACCIDENT FOR SOUND COMPOSITION

This accident involved both large and smaller vehicles with significantly different engine sounds. The impact to the pickup truck and subsequent vehicles was severe and resulted in broken metal, broken glass (from several vehicles), blown tires, fluid spills, and fire. There were a total of 4 distinct impacts, three in line and one between the first tractor-trailer and a jeep wrangler that happened against the side barrier. Pre impact tire marks are present as well as tire marks and gouge marks from post collision movement of the impacted vehicles. In addition, some debris from the pickup truck was deposited on the roadway. Since this accident involved multiple impacts between vehicles, several sound events of crashes will be heard. Sound samples are available for most of the potential sound sources listed in this analysis. The following is a list of the sounds in the accident based on this analysis:

- yaw mark sounds
- glass breaking
- metal collapsing
- tire blow outs
- metal dropped on roadway
- scraping of metal on concrete
- engine noise
- Tire turbulence on pavement
- fluid spilling
- fire
- background noise

4.3 ANALYIS OF THE ACCIDENT ENVIRONMENT

The speed limit on this roadway was 70 mph so there would have been significant sound pressure from the air turbulence of the moving vehicles. A heavily wooded area surrounds the impact area, but the volume of this area is too large and open to create a noticeable echo, though there would probably be some extra propagation of sound in the form of reverberation. The road is concrete and there is a concrete wall on the side opposite camera location. This suggests that higher frequency sounds will be reflected not absorbed. The distance from camera position one to camera position two is approximately 300'. This requires an adjustment in the perceived decibel level when the cut is made in the animation. Since vehicles pass the camera, a perceived change in both frequency (Doppler) and sound level would occur. Due to the size of the highway and the proximity of both direction travel lanes, a significant amount of background noise would be present.

Sound Samples Collected:

- Tire and yaw mark sounds
- Shattering glass

- Torn metal
- Popped tires
- Dropped Metal
- Metal scraping on concrete
- Engine noise
- Dripping fluid
- Fire

Sound principles Applied:

- 2.2.1) Pitch change of traveling sound sources
- 2.2.2) Sound Propogation Outdoors
- 2.2.6) Ambient sound levels

Sound sources were brought into the sound-editing program and synchronized to their respective event. The dB levels of the sounds were adjusted according to their frequency spectra and the sound sequence was reviewed for consistency and clarity. One camera location (the closest) was chosen as a fixed dB level, so that an adjustment would be made for shifting to the other camera. Using the attenuation of sound equation, and assuming a $Q(\phi)$=1, the sound level at the farther camera was decreased by 12dB. (A=20*log(30'/130') = 12dB. The ambient noise level was determined to be approximately 70dB for the distance of the first camera.

4.4 COMPARISON TO ACTUAL CRASH TESTS

Figure 8 shows a comparison of the resultant sound composite to a real world crash test between a tractor-trailer and a passenger car. While the crash test and the accident being reconstructed are obviously different, there are several patterns that provide a useful comparison.

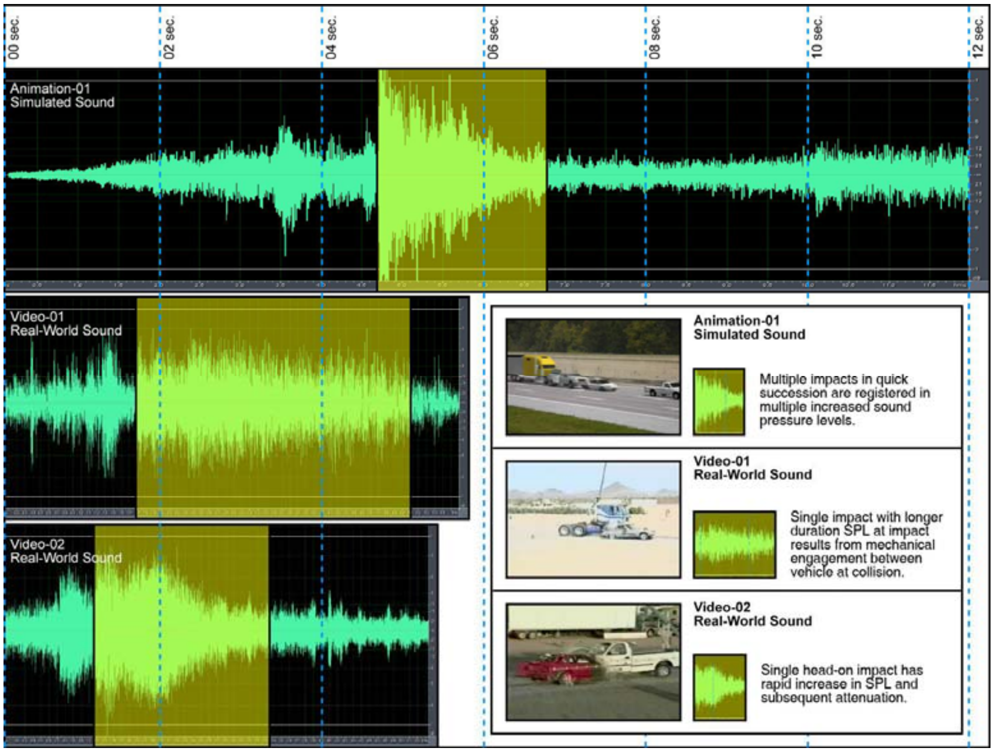
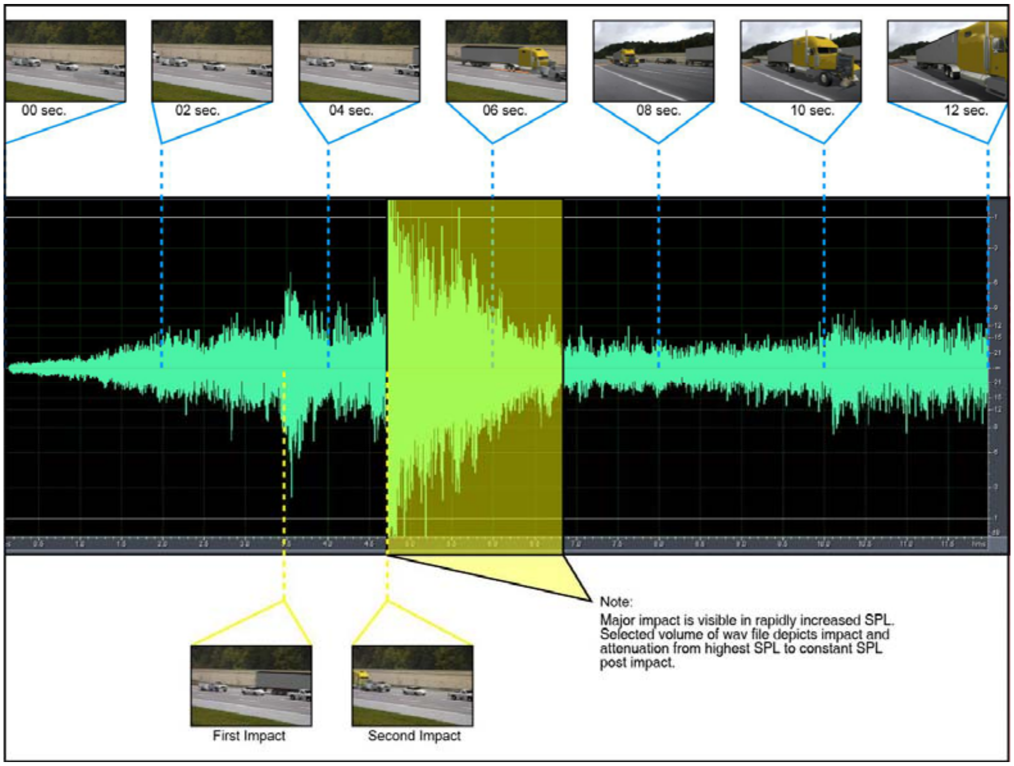


Figure 11 - Comparison of animation sound to crash test sound

In the crash test, background noise from the air turbulence underneath the tractor-trailer is represented in the large sound pressure levels pre-impact. This is comparable to the ambient noise levels seen in the sound sequence of the animated reconstruction sound wave. It should be noted that there is no engine noise from the truck in the crash test, only the noise from the track mechanism that propels the truck. This winding mechanism is audible and produces an amount of noise comparable to the sound of a truck engine. This helps make the overall sound event a close parallel to an actual accident involving the same vehicles. Also in the crash test, at impact, there is a significant gain in dB level that is mirrored in the animated reconstruction sound sequence. This same pattern of dB gain is repeated for each of the distinct impacts, though at a lesser magnitudes since the speeds of the vehicles at subsequent collisions is diminishing resulting in less sound pressure. Attenuation of the sound after impact is maintained according to analysis of sound in an actual accident and to the decay equations for sound as depicted in Figure 9.



Note:
Major impact is visible in rapidly increased SPL. Selected volume of wav file depicts impact and attenuation from highest SPL to constant SPL post impact.

Figure 12 - Frames from multi-vehicle accident

5 CONCLUSION

5.1 SUMMARY OF METHODOLOGY

Vehicle accidents themselves may be common, but the specific circumstances of each accident are inherently unique. The numbers of vehicles differ; the impact configuration, crash pulse, and component interaction all change from accident to accident. The environment in which the accident occurs is also unique. Concomitantly, the experience of sound in each accident is equally unique. Even the location of the witness can greatly alter the experience of sound.

All of these factors must be considered when compositing sound for an animated accident reconstruction. Sound in an animation can provide significant understanding to an animated reconstruction and the viewer would benefit from the addition of such sound. Not all accident reconstruction cases require animations. And not all animations require sound. However, sound can be important in communicating certain issues which are difficult with visuals only. For instance, the level of severity in a car crash can be communicated through an animation with sound much better than the same animation without sound. Appreciating the level of severity is a combination of both the visual reconstruction and the audible response of the impact. Since data is informing multiple senses, sight and sound, better information is being provided to the viewer. Sound also adds a spatial dimension to an animation since sound can communicate distance through echoes, reverberation and delays. Sound also marks important time related events. For instance, sound can help communicate the time differences between first contact, maximum penetration and separation through a creative and accurate application of acoustical principles. Were the techniques developed even more, it is even possible to imagine acoustical principles in this paper being used to analyze witness statements, or determine possible acoustical events that play into driver perception and reaction in a vehicle accident. Couple this need for sound with a methodology rooted in physics and the specific details of the accident and the final product is an experience that is an accurate representation of sound at the time of the accident.

While the acoustical principles and equations in this methodology are accepted in the acoustical industry, the accuracy of the proposed method has not yet been experimentally validated. Empirical testing may be performed in the future to asses the performance and accuracy of this method.

5.2 DIGITAL SOUND AND PLAYBACK

Compiled forensic animations with sound are played back to a viewer through the TV, laptop, CRT (Computer screen) Plasma screens, or projection equipment. Sound in animation, however, is not “live” and is an inherently different experience that hearing sound at the actual time and location of the accident. For this reason, sound in an animation is meant to augment the understanding of an accident, not replicate the experience of actually being a witness to the accident. Sound in animation is emitted through the speakers or headphones that are connected through the audio channels of the display device in which the animation is being played. This may occur for deposition, legal engineering conferences, video conferences, settlement conferences, and the courtroom. Noting the different conditions in which the animation will be played is useful in preparing the equipment and setup. Courtrooms, being larger venues, may require addition sound devices and speakers to make sure the sound quality and sound level are sufficient for clear audibility. Sound systems are available in from stereo audio to 7.1 surround sound audio. All of these provide a different listening experience and should be taken into consideration when compositing sound in an animation. The equations described in this methodology are based on the acoustical principles in real world conditions. The animations that utilize a sound sequence, however, are digital, and the scales for sound in the digital realm differ from those of the real world conditions. Digital sound editing software and the hardware that it uses have a sound level scale measured in dBFS, not dB(A). dBFS (Decibel Full Scale) measures digital sound levels that fall within acceptable clipping ranges of the sound hardware itself. Full Scale refers to the maximum peak voltage that the sound equipment can handle before clipping occurs[2,10]. The Full Scale range is defined by the sound equipment and differs from model to model.

Sound equipment may differ in quality and the acceptable sound level ranges below clipping depend on the quality of this equipment. But by default, the maximum sound level in dBFS is 0. 0 dBFS is the max sound level and all other sound levels are measured in negative. This difference is only in the fact that digital sound uses a scale that peaks at 0. Adjustments to the decibel levels in digital sound would follow the same rules as in real world conditions and the equations in the methodology work for digital sound in the same way. The scale simply starts at zero and works in negative numbers rather than positive number. When calculating decibel changes, one need only adjust for this difference.

5.3 LIMITATIONS IN EQUIPMENT

Though digital sound still works on the same logarithmic scales as sound in real world conditions, the hardware, or sound cards, used can determine the sound level ranges available in sound editing software. The sound level range of a sound card is determined by the following relationship[14]:

$$dB = 20 \cdot \log\left(\frac{amplitude}{32{,}768}\right) \tag{11}$$

Where $amplitude$ is a discrete number representing the maximum allowable amplitude for digital sound for that sound card. In a 16 bit sound card, for instance, the maximum range for amplitude is -32,768 to 32,767. Sound cards are available at various quality levels, from 8 bit to 32 bit. The quality of the sound card determines the maximum available sound level range. For example, an 8 bit card has a max sound level that is equivalent to 48 dB, well below the upper range of the human ear. As a result, a sound sequence may not have as dynamic a sound level range as a higher quality sound card. Higher quality sound cards, like 16 bit cards, can go up to 96 dB. The sound card is not the only limitation to the experience of sound though. Speakers, the acoustics of the room and the position of the viewer in relationship to the sound source will all have an impact on the experience and quality of sound. This fact produces a lowest common denominator effect. In other words, the quality of the sound is only as good as the lowest quality equipment in the process from obtaining digital sound samples to playing a final product on speakers. Needless to say, maintaining as high a quality throughout the sound production process is ultimately desired. As the equipment for sound recording and sound editing continues to improve, the equations and techniques of the methodology will also develop. Advances in sound editing will allow more control of a wider sound level range, frequency spectra, and other aspects of sound that are currently limited. This will allow additional equations and acoustical principles to be applicable and continually improve the physical accuracy of the sound sequence.

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