Detection of Vehicles with Studded Tires Using Acoustic Emission Sensors Mounted to Highway Bridges

Thomas Schumacher[1]; Christopher C. Higgins[2]; and Steven C. Lovejoy[3]

Abstract: Transportation agencies expend large amounts of money annually to maintain highway wearing surfaces. Wear depends mainly on axle weight, vehicle speed, temperature, surface type, and the type of tires mounted on vehicles. When studded tires are used, wear is increased significantly. Past studies on the use of studded tires have highlighted the need for a tool to better estimate the number of vehicles with studded tires that travel a road network. Currently, there is no such tool available. This paper presents a detection methodology using acoustic emission techniques to identify vehicles operating with studded tires. Data from an in-service test on a highway bridge were used for developing and evaluating two proposed detection schemes. It was found that using relatively simple detection algorithms, vehicles with studded tires could be discriminated reliably. Finally, a practicable integrated system is proposed that could be implemented for detection and monitoring of studded snow tire use on highway systems.

DOI: 10.1061/(ASCE)TE.1943-5436.0000062

CE Database subject headings: Tires; Vehicles; Probe instruments; Monitoring; Bridges; Highway.

Author keywords: Studded tires; Acoustic Emission; Monitoring; Real-time detection; Highway bridges.

Introduction

Transportation agencies expend large amounts of money annually to repair and replace highway wearing surfaces. A study by Brunette and Lundy (1996) estimated that total damage for 1994 due to studded tires in the State of Oregon's road network was about $70 million. A more recent study by Malik (2000) estimated expenditures for repairing studded-tire damage from 1994 to 2005 to total of about $103 million for the Oregon highway system alone. This estimate assumes average pavement design life and wear rate. The total number of vehicles with studded tires was estimated based on parking lot counting and telephone surveys. A more recent study was published by Zubeck and Larson (2004) and covers the socio-economic impact of studded tire use in Alaska. It was concluded that the use of studded tires in Alaska may actually have a positive impact on the Alaskan economy. The savings from avoided accidents were the most substantial benefit. However, relation between rutted pavements and summer hydroplaning accidents was not taken into account. Here as well, visual inspection and vehicle counting on parking lots was used to determine the stud usage rate. The most recent data published by the Washington State Department of Transportation [Washington State DOT—Materials Laboratory (WSDOT) 2006] have revealed that damage from the use of studded tires on Portland cement concrete highways alone resulted approximately $18 million of additional cost within the state of Washington, with damage for asphalt concrete much higher.

Currently, no automated tools are available to accurately identify the number of vehicles with studded tires traveling on a highway network. It would be of great interest to estimate the number of vehicles with studded tires that operate after the legal dates. Enforcing these dates could be a first start to reduce damage on the infrastructure. Presented in this paper is the development and evaluation of detection methods based on the acoustic emission (AE) technique. An integrated system that enables automated real-time detection of vehicles with studded tires is proposed. This tool could be employed to establish statistics about the use of studded tires and could further be used as an enforcement tool to identify studded tire use past the allowable use date.

Background

Problems Associated with the Use of Studded Tires

Studded tires are winter tires that are equipped with studs made of metal or plastic materials designed to improve traction for winter driving. The studs protrude from the tire surface and are usually made of tungsten carbide, a very high-strength metal. They are held in place by metal jackets inserted in the tire. Detailed information about studded tires, damage mechanisms to wearing surfaces, and state regulations can be found in a study published by the Washington State Transportation Center (TRAC) (1999). For the state of Oregon, Brunette and Lundy (1996) estimated the wear rate on asphalt concrete and Portland cement concrete to be about 0.86 and 0.20 mm per 100,000 studded tires passes, respectively. While benefits have been identified for users, problems have arisen with the use of studded tires including

1. Ruts are produced in rigid (Portland cement concrete) as well

[1]Postdoctoral Research Associate, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR 97331 (corresponding author). E-mail: th.schumacher.2@gmail.com

[2]Professor, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR 97331. E-mail: chris.higgins@oregonstate.edu

[3]Senior Research Engineer, Oregon Dept. of Transportation, Bridge Engineering Section, Salem, OR 97301. E-mail: steven.c.lovejoy@odot.state.or.us

Note. This manuscript was submitted on September 24, 2008; approved on April 24, 2009; published online on April 27, 2009. Discussion period open until October 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering***, Vol. 136, No. 5, May 1, 2010. ©ASCE, ISSN 0733-947X/2010/5-480–487/$25.00.

as flexible (asphalt concrete) pavements that fill with water and ice and can cause hydroplaning and slipping;
2. May polish aggregates and reduce friction;
3. May make driving more difficult during dry conditions;
4. Loosened wearing surface particles become airborne dust and contribute to air pollution;
5. Increased noise level; and
6. On dry and wet surfaces (no ice), regular winter tires have better traction than studded tires.

In most states where studded tires are allowed, there are date restrictions on when it is legal to drive with studded tires. Wyoming, Colorado, and New Mexico allow the use of studded tires without restrictions. Unfortunately, there are no data available on the damage caused by studded tires in these states. In Oregon, tires equipped with lightweight studs are legal between November 30 and April 3. In the state of Washington, it is November 1 to March 31. Motorists are encouraged to use studded tires only when necessary because of the increased damage they cause to roadways; however few dismount and remount studded tires during the permissible season.

AE Monitoring

AE are the result of a sudden spontaneous strain release within a solid body, i.e., the formation of a crack. A stress wave is generated, traveling from the source origin away to the surface of the body where it can be detected by sensors. Other names for AE include *stress wave emission* or *microseismic activity* [American Society of Nondestructive Testing (ASNT) 2005]. Formally defined, AE is the *term used for transient elastic waves generated by the release of energy within a material or by a process* [European Committee for Standardization (CEN) 2000]. The AE technique has been established as a means to monitor structural deterioration, e.g., material fracture, and has hence found applications in material science and structural health monitoring, e.g., of bridges.

The general principle of AE data acquisition is that emitted stress waves are recorded, stored, and then analyzed. Piezoelectric based sensors mounted to the surface of the test object are typically used for AE monitoring, which produce a voltage-versus-time signal from the dynamic surface motion (ASNT 2005). A thin layer of high vacuum grease is typically used as a couplant between sensor and concrete surface. The generated voltage signal output is proportional to the surface pressure and dependent on the size and damping characteristics of the sensor. Ideally, a sensor should have a very flat response over the whole frequency range. This is necessary for wave form analyses, but sensors of this kind tend to be not very sensitive which makes it difficult to detect AE signals in reinforced concrete (RC) at a distance of more than a few meters. Resonant sensors are sensitive at their resonant frequency and have proven to work well for AE signal detection in RC (Lovejoy 2006; Schumacher 2008). This signal is then intensified by a preamplifier. Usually not only one but several sensors are deployed and record data in parallel. In order to store data on the hard disk, the analog sensor signals must first be digitalized. Typically, AE data are not acquired continuously, since that would yield enormous data files which would be hard to interpret. Preselected criteria are used to trigger the system for individual AE burst signals from which descriptive parameters and wave forms are then extracted. For this study, the most important parameter was *AE hit amplitude*, which is the maximum voltage measured during a discriminated AE burst signal and represented on a decibel scale. All this is done in real time and requires a powerful data acquisition system. Fig. 1 schematically illustrates the elements of a typical AE data acquisition system. In this case, the stress wave is released from within the body. For the case of studded tires, the source is introduced on one side of the body, then travels through it and is eventually detected by the sensor on the opposite side of the body.

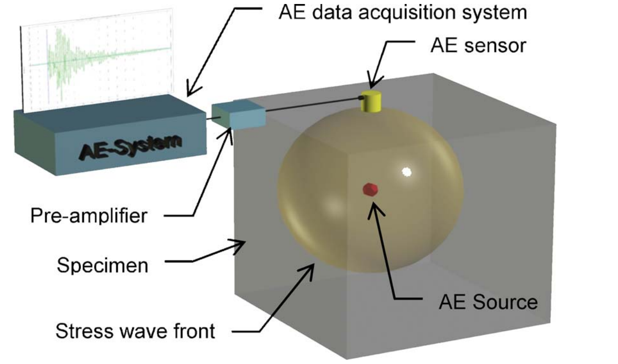

Fig. 1. Example of a typical AE system setup (only one AE sensor shown for clarity)

In structural health monitoring, a source such as the discussed one caused by studded tires would be considered as noise as it is generated from an external artificial source which should be filtered out as it can significantly bias damage detection algorithms. For this study, however, it becomes the source of main interest. As will be shown in this paper, it is fairly uncomplicated to detect vehicles with studded tires with high reliability.

Field Experiment

Test Site and Procedure

The data used in this paper were collected from an in-service bridge under ambient traffic and controlled loads. The bridge is Bridge No. 7863 on Interstate 5 in Cottage Grove, Ore. and the tests were conducted on March 26/27, 2006. A series of ten test runs with a 22.7-t (50,000 lb) total weight three-axle dump truck were conducted with three different speeds and the response of varies sensors recorded. The bridge was closed for other traffic each time. In between the test runs, the data acquisition system was recording as well, collecting data from ambient traffic.

Fig. 2 shows a photo taken from the northwest corner of the bridge. The bridge is a conventionally reinforced deck girder type bridge commonly found in Oregon and was built in the 1950s. It consists of three spans plus a short cantilever span on the south side. The center span length is 25.30 m (83 ft), the adjacent spans are 19.81 m (65 ft) long, and the cantilever span length measures 3.96 m (13 ft). The wearing surface consists of a hot-mix asphalt overlay with a thickness of approximately 76 mm (3 in.).

Data Acquisition System and Instrumentation

The test was conducted to determine service-level strains on reinforcing bars and diagonal crack motion, as well as AE activity on an interior girder on the bridge. Strain was monitored on a vertical reinforcement bar (stirrup) crossing a diagonal crack with a 3.2-mm (0.125 in.) strain gauge as well crack motion perpendicular to that same crack with a 12.7-mm (0.5 in.) linear dis-

Fig. 2. Photo of the tested bridge

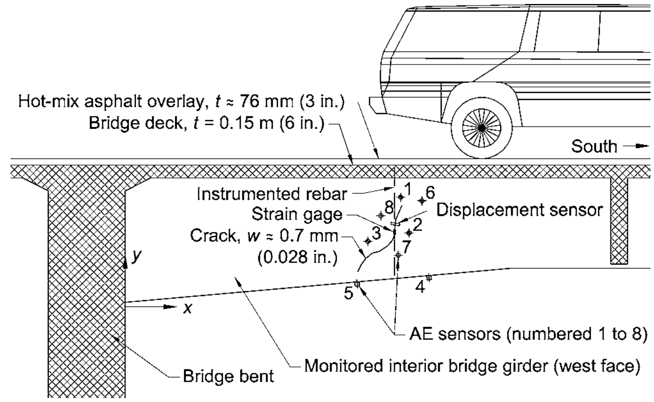

Fig. 3. Elevation view of monitored interior girder with sensor locations

placement sensor. A sampling rate of 10 Hz was used. The instrumentation plan is presented schematically in Fig. 3. AE sensors are numbered 1 through 8.

For AE data acquisition, an eight-channel Vallen AMSY-5 system was used. All channels have built-in analog band-pass filters with frequency limits of 20 (low) to 850 kHz (high) for Channels 1, 7, and 8, and 40 (low) to 850 kHz (high) for Channels 2–6. The dynamic range of the system is 16 bit and the maximum sampling frequency 10 MHz. For this field test, wave forms were stored for all AE burst signals that crossed a threshold of 40 dB. The sampling rate was set to 2 MHz. Full AE wave forms were stored over a total length of 1,024 μs with 400 μs before the threshold crossing. The AE sensors used for this test were KRNi060. They show resonant behavior with peak responses at around 60 and 200 kHz. These sensors were chosen because of their high sensitivity found in laboratory experiments (Lovejoy 2006; Schumacher 2008). AE sensor location coordinates are provided in Table 1.

Data Analysis Methods

An AE system using low-frequency sensors is desirable because wearing surface and concrete have large damping characteristics. It is assumed that each individual stud impact causes a stress wave to initiate and propagate through the structure. This occurs at a frequency of about 1.3 kHz or every 0.77 ms considering a midsized car traveling with a speed of about 90 km/h (55 miles/h), which is in the audible range of the human ear. During the load test, audible sounds were produced by vehicles with studded

Table 1. AE Sensor Location Coordinates

Sensor number	Location on face	Metric x (m)	Metric y (m)	Metric z (m)	U.S. customary x (in.)	U.S. customary y (in.)	U.S. customary z (in.)
1	West	3.274	1.295	0.211	128.9	51.0	8.3
2	West	3.371	0.876	0.208	132.7	34.5	8.2
3	West	2.883	0.775	0.221	113.5	30.5	8.7
4	Bottom	3.607	0.368	0.076	142.0	14.5	3.0
5	Bottom	2.753	0.284	−0.104	108.4	11.2	−4.1
6	East	3.526	1.252	−0.206	138.8	49.3	−8.1
7	East	3.244	0.610	−0.213	127.7	24.0	−8.4
8	East	3.035	1.080	−0.218	119.5	42.5	−8.6

tires operating on the bare surface of the bridge deck that were easily identified and distinguished by the research team. This audible signature is well known to experienced bridge and transportation engineers in regions where studded tires are used. Coincident with identification of the audible signature of the studded tires, the AE responses from this source were observed to be unique and different from other sources of AE. Subsequently, several studded-tire vehicle occurrences were identified and correlated to coincident AE patterns for further analysis.

The present AE sensor array employing eight transducers was more extensive than is actually required to identify vehicles with studded tires but commonly used for structural health monitoring. To investigate the feasibility of an automated one-channel detection system, only one sensor was considered (Channel 8). Channel 8 was located on the web, approximately 0.45 m (17.5 in.) below the deck. It is equipped with an analog band-pass filter that rejects frequencies below 20 kHz and above 850 kHz. Comparing the different channels, those with lower cutoff frequencies (20 kHz rather than 40 kHz) like Channel 8, seemed to pick up AE from studded tires much better underlying the importance of having low-frequency AE sensors.

Fig. 4 shows an example of recorded data from the passing of a 22.7-t (50,000 lb) three-axle test truck (a), for a passenger car equipped with studded tires (b_1) and a similar passenger car without studded tires (b_2). The top row graphs illustrate measured rebar strains (green line) and AE hit amplitudes as purple dots. The bottom row graphs show the number of detected AE hits, where the red bars represent AE hits and the green line cumulative AE hits. The bin size was set to 0.2 s. The truck's speed was about 85 km/h (52 miles/h); the cars' speeds were assumed to be in the same range. As can easily be seen in Fig. 4, the test truck (a) produces a large strain response with relatively low-amplitude AE hits over a time frame of approximately 2 s. On the other hand, the passenger car with studded tires (b_1) causes a small strain response accompanied by a cluster of very high-amplitude AE with virtually no low-amplitude events over a very short time frame. The passenger car with regular tires produced a small strain response without any AE.

To summarize, vehicles equipped with studded tires were found to produce a unique response on the AE sensing system with the following characteristics:

1. Localized clusters of high-amplitude AE hits (some signals clipped due to saturation);
2. AE events occur within a very short time window; and
3. Small rebar strain readings.

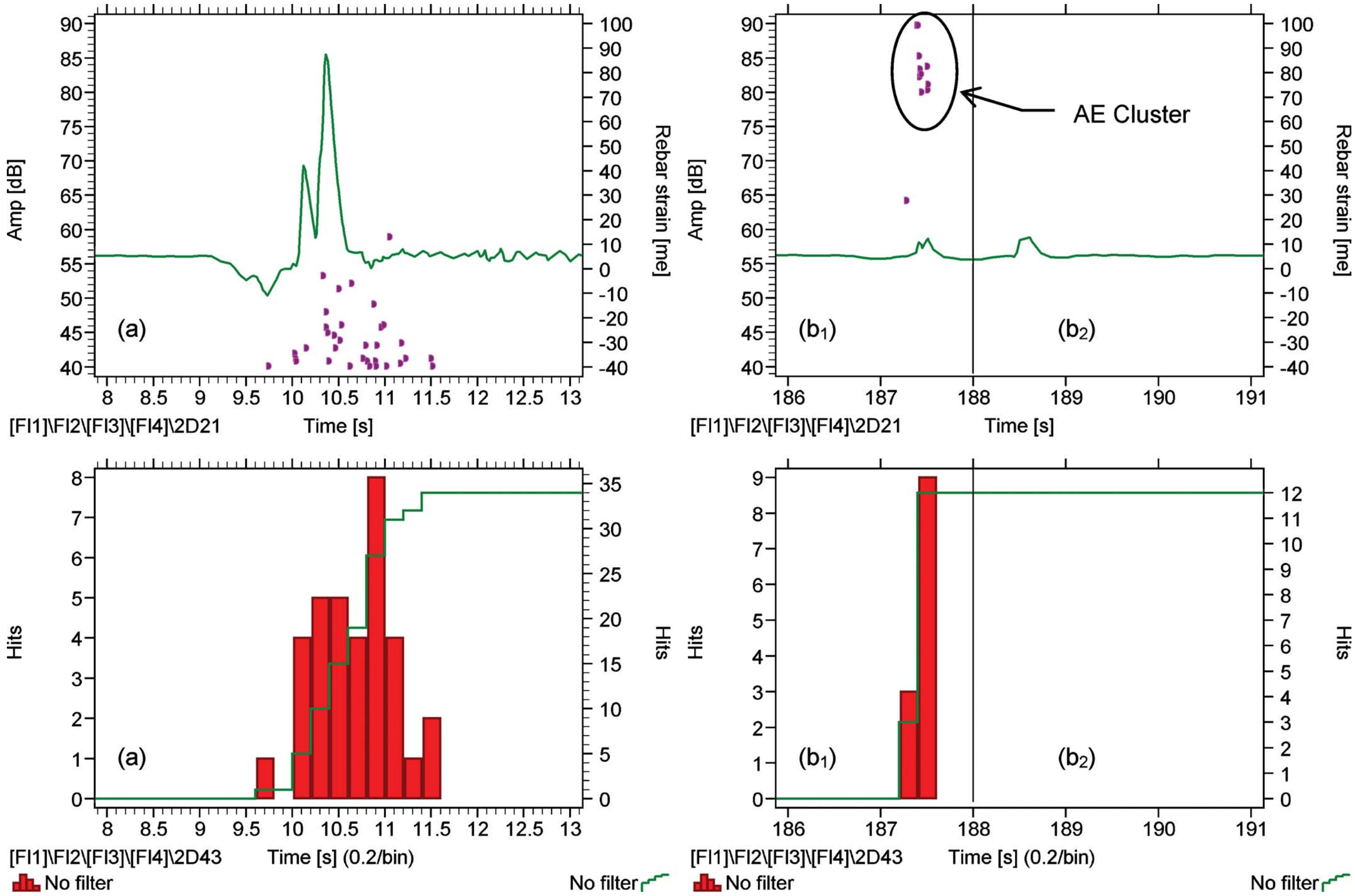

Fig. 4. Example data: test truck (a) and passenger car with (b_1), and without studded tires (b_2)

Due to the use of resonant AE sensors, there was no significant difference in the frequency response between AE signals caused from vehicles with and without studded tires. The response of such sensors is usually governed by the characteristics of the sensor and not the source.

In the following three sections, methods for data analysis are presented. Two different schemes to detect vehicles with studded tires according to the previously stated characteristics are presented and then compared.

Computation of AE Hit Amplitudes

AE hit amplitudes are defined as $A[\mathrm{dB}]=20\cdot\log(A[\mathrm{mV}])+60$, where $A[\mathrm{mV}]$ is the maximum voltage reading from one discriminated AE burst signal. An example of a typical AE wave form is illustrated in Fig. 5. This output voltage is produced by the sensor's piezoceramic element and proportional to the surface particle motion. One issue that may arise is that the AE signals can become clipped due to channel saturation for the studded tire case. Clipped wave forms may lead to some skewing of the data for the case of the vehicles with studded tires where saturation is achieved. In this study, this was not further considered because the methods appear to be robust enough as proposed.

Detection Scheme 1: Mean AE Hit Amplitudes

For this scheme, mean AE hit amplitude values are computed for each discrete vehicle crossing. In addition to mean amplitude values μ, SDs σ were computed as well. A significant difference was found between a truck and a passenger car with studded tires in terms of average the AE hit amplitude. Fig. 6 shows the statistics for the AE hit amplitudes for a truck (a) and a passenger car with studded tires (b_1) computed for the same data set presented in Fig. 4, where n represents the number of AE hits included in the computation. Because there are no low-amplitude events for case (b_1), the mean value is very high and the coefficient of variation ρ expected to be small. The coefficient of variation is defined as $\rho=\sigma/\mu$. Even if the maximum AE hit amplitudes are the same for both cases, the mean for case (a) will always be

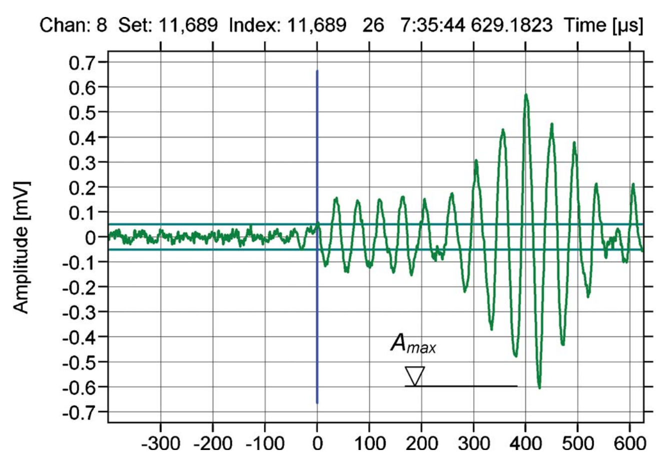

Fig. 5. Typical AE signal waveform

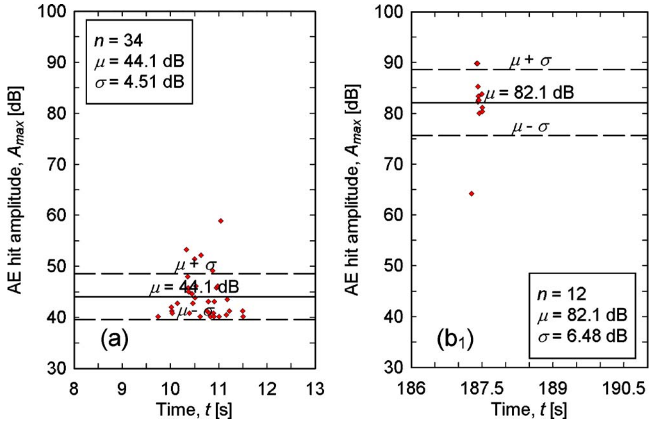

Fig. 6. Mean AE hit amplitudes for the test truck (a) and the car with studded tires (b_1)

lower and the spread much larger than for case (b_1) because it contains low-amplitude events. Therefore, this simple computation should be robust and work very well to detect vehicles with studded tires. However, a more complex complementary analysis procedure for this data set is presented in the following section.

Detection Scheme 2: b-Value Analysis

The observations from Fig. 4 indicates that the so-called *b-value analysis* or *amplitude-frequency distribution analysis* may provide an additional means to characterize vehicles with studded tires. The original relationship was established by Gutenberg and Richter (1949) to relate the annual number (mean frequency) of earthquakes with corresponding earthquake magnitudes. More recently it has been adapted to analyze slope-stability in geotechnical and material science applications (Shiotani and Ohtsu 1998; Rao and Prasanna Lakshmi 2005). The magnitude-frequency distribution relationship is defined as

$$\log_{10}(N) = a - b \cdot M_L \tag{1}$$

where M_L=magnitude of an event on the Richter scale; N=number of events that lie within $M_L \pm \Delta M_L$; and a and b=empirical constants. The constant b represents the slope of the magnitude-frequency diagram. The basic concept is that this b value (the slope) decreases when damage becomes more localized. For

Table 2. Summary of Results

Parameter	(a)	(b_1)	(b_2)
Max. AE amplitude, A_{max} [dB]	59.0	89.8	0
Average AE amplitude per event, μ [dB]	44.1	82.1	0
Total hits during event, n [-]	34	12	0
Approx. time frame [s]	2	0.2	—
Estimated b-value, b [-]	1.90	0.61	—
Standard error of estimated b-value, S_E [-]	0.33	0.17	
Maximum strain, ε_{max} [με]	82	7	8
Minimum strain, ε_{min} [με]	−16	−1	−2

RC, b-value analysis has been used by several researchers to characterize structural deterioration of RC (Shiotani et al. 2000; Colombo et al. 2003; Kurz et al. 2006; Schumacher 2008). From these studies, it was found that the b value drops well below a value of about 1 when the system becomes unstable, i.e., during formation of a macrocrack. In AE, commonly the maximum hit amplitude in [dB] is multiplied by a factor of 1/20 and replaces the earthquake magnitude M_L. This yields b values in the same range as those seen in seismic applications. It appears that this b value could be used to discriminate AE event clusters caused by passenger cars with studded tires since the amplitude distribution is very distinct and different from AE clusters created by vehicles without studded tires, hence the slope or b value should be different as well.

Fig. 7 illustrates AE amplitude-frequency distribution plots for the test truck (a) and the vehicle with studded tires (b_1). The estimated b values of each amplitude-frequency distribution plot were estimated with Matlab employing a first order polynomial curve fit over the mean ± one SD of the AE amplitudes as suggested by Rao and Prasanna Lakshmi (2005). Standard errors are given as $S_E = b/\sqrt{n}$, where n is the number of samples used to estimate the b values. Notice the significant difference between estimated b values of the test truck (a) and the vehicle with studded tires (b_1). It can also be observed that the distribution line is highly nonlinear for the vehicle with studded tires (b_1). This will be explored more deeply in the future as it may be used as an additional indicator to detect studded tires.

In Table 2, key results from the previous analyzes are summarized. The differences in the sensor responses are easily recognizable. Both detection schemes, mean AE amplitudes as well as

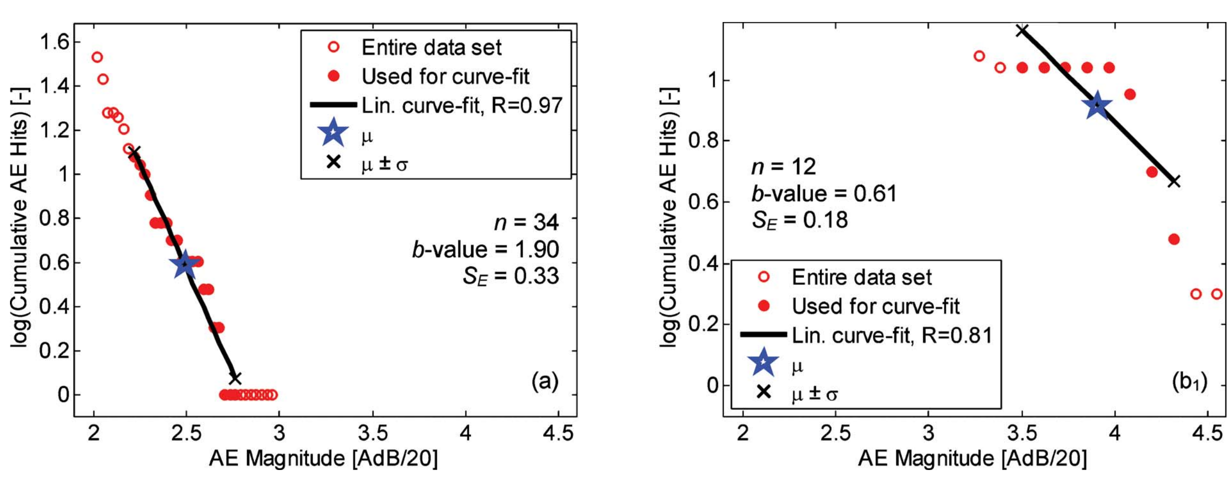

Fig. 7. Amplitude-frequency distributions for test truck (a) and passenger car with studded tires (b_1)

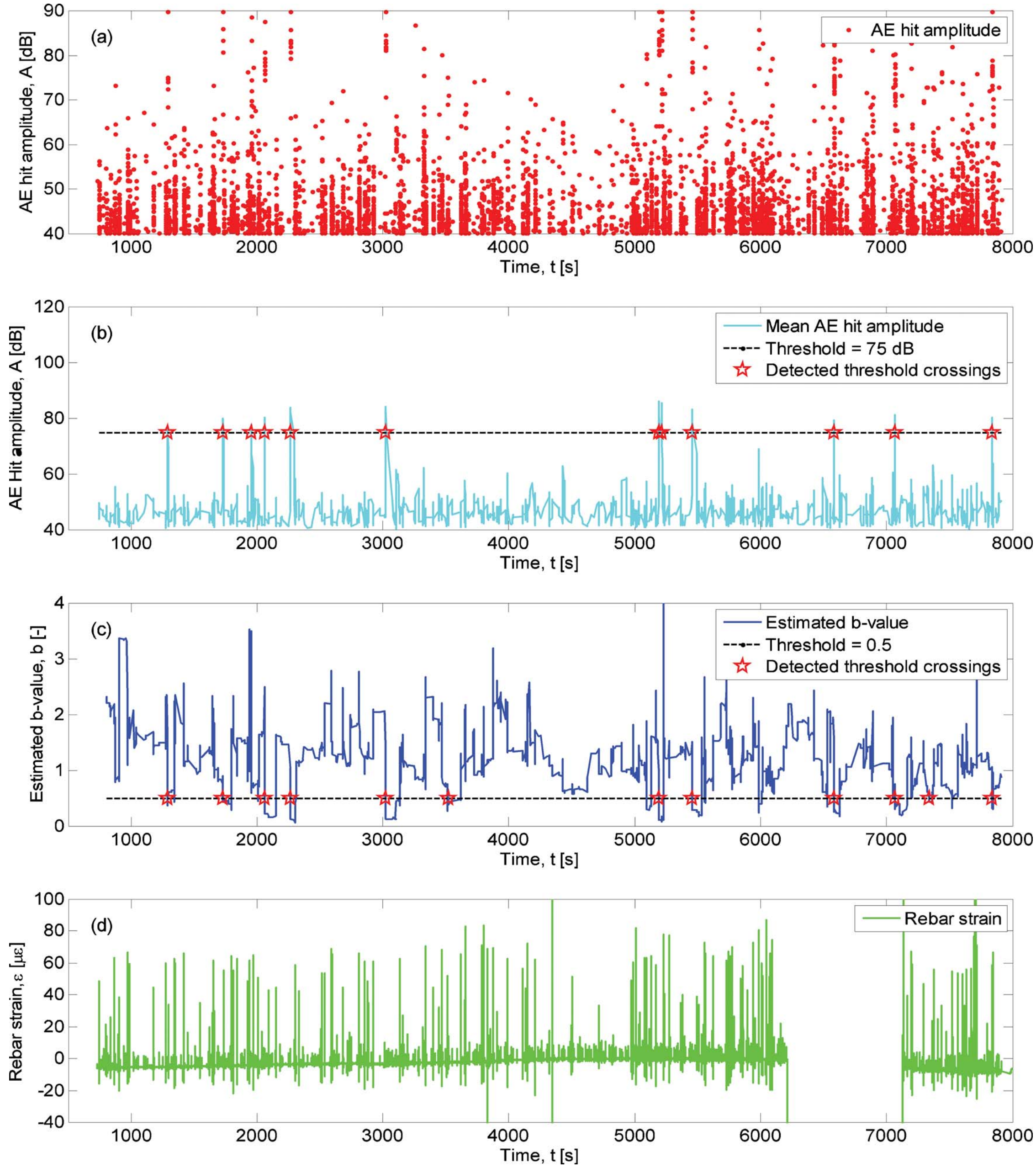

Fig. 8. Results for continuous evaluation

b-value analysis appear to be appropriate means to characterize vehicles with studded tires. Complementary, strain measurements can further confirm the weight magnitude and type of vehicle that is passing by the detection system.

Analyzing clusters of AE events produced by isolated vehicle crossing is one possible way to identify vehicles with studded tires. The only problem here is that these events have to be discriminated and that can be difficult especially with dense traffic. Another alternative method is continuous evaluation of real-time AE data. The implementation of this approach is presented in the next chapter.

Continuous Evaluation or Real-Time Monitoring

The two previously presented analysis procedures were then implemented in Matlab and applied to the entire in-service test data. Mean AE hit amplitudes and SDs were computed over five values back in time. For the critical threshold, an AE amplitude value of 75 dB was found to work well for detection of vehicles with studded tires. *b* values were estimated over a total of 50 AE hit amplitude values back in time. A threshold was set to a critical *b* value of 0.5 as trigger criteria for the detection of vehicles with studded tires. Once this critical *b* value is crossed, it has to increase first above that same value before it is ready to trigger again. Verification with strain readings is then performed and has to be within a certain range that is characteristic for passenger cars with studded tires. For this study, the maximum strain reading had to be between 1 and 20 $\mu\varepsilon$. Because every structure is unique and has different material properties, threshold values will have to be selected on a case by case basis.

Results from the continuous evaluation are illustrated in Fig. 8 where (a) shows AE hit amplitudes recorded by the AE data acquisition system, (b) computed mean AE hit amplitudes (Scheme

Table 3. Summary and Comparison of Detection Methods

Event number (-)	Manually time (s)	Min. strain ε_{min} ($\mu\varepsilon$)	Max. strain ε_{max} ($\mu\varepsilon$)	Scheme 1 time (s)	Scheme 2 time (s)
1	1290	−1	7	1291	1290
2	1726	−1	7	1726	1726
3	1955	−1	8	1955	—
4	2059	−2	11	2059	2059
5	2264	−2	9	2264	2264
6	3023	−1	5	3023	3023
7	—	−2	6	—	3524
8	5190	−1	7	5190	5190
9	5217	−1	10	5216	—
10	5457	−1	10	5457	5457
11	6579	n/a	n/a	6579	6579
12	7069	n/a	n/a	7069	7069
13	—	−1	8	—	7338
14	7836	−3	16	7836	7836
Detections, total	12	—	—	12	12
Correct detections	—	—	—	12	10
Not detected, missed	—	—	—	0	2
False detections	—	—	—	0	2

1), and (c) estimated *b* values (Scheme 2). Strain measured on the stirrup is illustrated in (d). Note that strain data are missing between approximately 6,200 and 7,100 s due to a small technical issue. Table 3 summarizes the detection results and compares them with the ones determined by manually searching through the AE hit amplitudes and strain readings for vehicles with studded tires.

As can be seen in Table 3, 12 events were found manually to qualify as "passing vehicle with studded tires." Detection Scheme 1 (mean AE amplitudes) did an excellent job in identifying all manually determined events. Problems arise for detection Scheme 2, based on *b* values when detections have to take place closely spaced in time. This is because *b* values need some "recover time" after triggering, i.e., they have to return to a higher value of 0.5 first, before it is ready to trigger again. This problem does not exist for the mean AE hit amplitude approach (Scheme 1) since the averaging is only over five AE hit amplitudes. Also, for two instances, the *b*-value scheme falsely detected vehicles with studded tires. However, the method may still be used as a complementary tool, although more fine tuning is needed. The fact that *b* values are sensitive to vehicles with studded tires is important by itself because this could interfere with a structural health monitoring system that monitors the structural integrity of a bridge.

Recommendations for an Integrated Detection System

A practicable implementation of a detection system for vehicles with studded tires is described here. As shown earlier, a conventional one-channel AE detection system would be sufficiently robust to detect passing vehicles with studded tires. An AE sensor would be mounted to the deck soffit to maximize detection. This sensor would be connected via coax-cable to the single-channel AE system located in an accessible and secured enclosure. Handheld one-channel AE systems are commercially available that would work for this kind of application. Additionally, a strain gauge could be used as a supplemental parametric input for verification of the vehicle load effect. However, the writers suggest the use of a wireless sensor network employing so-called motes would be especially energy efficient and low maintenance for this application. A mote is a complete measurement and communication unit that connects to the sensor via a short cable and communicates with a base station via radio transmission (Grosse et al. 2006). The base station would be located at the site and be triggered by predefined threshold values of the mean AE hit amplitudes. From here, the data would be either stored locally at the site to be manually collected or streamed to a central server (via cable, radio transmission, or cell phone) for continuous observation or analysis. Alternatively, messages could be sent regularly to the bridge owner as to cumulative counts and times of occurrences. Further, a camera positioned over the roadway could be triggered to capture images of the identified vehicles for reference. At the present time, the technologies exist and are practically obtained for such systems and at reasonable cost.

Conclusions

The use of studded tires has become of increasing concern to transportation agencies due to the damage caused to pavements, and limited funds available for repair and replacement. Large annual expenditures are made in jurisdictions which permit studded tires to maintain pavements. Currently no tools are available to automatically detect and report vehicles with studded tires. An integrated system to detect vehicles with studded tires passing over a highway bridge is proposed. Piezoelectric sensors attached to the bridge members can detect and record stress waves that are emitted when vehicles with studded tires pass over the bridge. Discrimination of these stress waves is possible because they were found to significantly differ from trucks and vehicles that have no studded tires. It was found that simple mean AE hit amplitude schemes work very well and are sufficient to detect vehicles with studded tires that pass over a bridge. Nevertheless, physical measurements as rebar or surface strain readings are recommended as complimentary measurement of load magnitude. Additional analysis methods, such as *b*-value analysis, are sensitive to vehicles with studded tires as well, but need some further fine tuning.

A simplified single-channel system could be practicably deployed for detection and reporting and would allow for collection of statistical data to better estimate pavement life and wear ratio. AE systems offer the opportunity for more reliable data on the number of studded tires in operation and the time periods of use on a particular highway. That can be used primarily to improve design and maintenance of road surfaces. The system could further be extended for use as an enforcement tool of legal studded-tire operating dates.

Acknowledgments

The support and sponsorship for this study by the Oregon Department of Transportation is greatly appreciated.

References

American Society of Nondestructive Testing (ASNT). (2005). *Nondestructive testing handbook, Volume 6: Acoustic emission testing*, ASNT, Columbus, Ohio.

Brunette, B. E., and Lundy, J. R. (1996). "Use and effects of studded tires on Oregon pavements." *Transp. Res. Rec.*, 1536, 64–72.

Colombo, S., Main, I. G., and Forde, M. C. (2003). "Assessing damage of reinforced concrete beam using '*b*-value' analysis of acoustic emission signals." *J. Mater. Civ. Eng.*, 15(3), 280–286.

European Committee for Standardization (CEN). (2000). "Nondestructive testing-terminology—Part 9: Terms used in acoustic emission testing." *EN 1330-9*, Brussels.

Grosse, Ch. U., Glaser, St. D., and Krüger, M. (2006). "Condition monitoring of concrete structures using wireless sensor networks and MEMS." *Proc., SPIE, Smart Structures and Materials: Sensors and Smart Structures Technology for Civil, Mechanical, and Aerospace Systems*, Vol. 6174, SPIE, Bellingham, Wash., 407–418.

Gutenberg, B., and Richter, C. F. (1949). *Seismicity of the Earth and associated phenomena*, Princeton University Press, Princeton, N.J.

Kurz, J. H., Finck, F., Grosse, Ch. U., and Reinhard, H.-W. R. (2006). "Stress drop and stress redistribution in concrete quantified over time by the *b*-value analysis." *Struct. Health Monit.*, 5(1), 69–80.

Lovejoy, St. (2006). "Development of acoustic emissions testing procedures applicable to conventionally reinforced concrete deck girder bridges subjected to diagonal tension cracking." Ph.D. thesis, Oregon State Univ., Corvallis, Ore.

Malik, G. M. (2000). *Final Research Report, Oregon Department of Transportation (ODOT)*, Studded Tires in Oregon, Salem, Ore.

Rao, M. V. M. S., and Prasanna Lakshmi, K. J. (2005). "Analysis of *b*-value and improved *b*-value of acoustic emissions accompanying rock fracture." *Curr. Sci.*, 89(9), 1577–1582.

Schumacher, T. (2008). "Acoustic emission methods applied to conventionally reinforced concrete bridge girders." *Final Research Rep. No. SPR 633*, Oregon DOT (ODOT), Salem, Ore.

Shiotani, T., and Ohtsu, M. (1998). "Prediction of slope failure based on AE activity." *Proc., Acoustic Emission: Standards and Technology Update*, ASTM, West Conshohocken, Pa., 156–171.

Shiotani, T., and Yuyama, S., Li, Z. W., and Ohtsu, M. (2000). "Quantitative evaluation of fracture process in concrete by the use of improved *b*-value." *Proc., Conf. on Non-Destructive Testing in Civil Engineering (Seiken Symposium No. 26)*, Elsevier, Tokyo, 293–302.

Washington State DOT—Materials Laboratory (WSDOT). (2006). "Pavements and studded tire damage." Olympia, Wash., ⟨http://www.wsdot.wa.gov/biz/mats/pavement/PavementsStuddedTiresFinalv2.pdf⟩ (Aug. 25, 2008).

Washington State Transportation Center (TRAC). (1999). "A synthesis on studded tires." *Final Research Rep., Agreement T9903*, *Task 92*, Washington State DOT, Olympia, Wash.

Zubeck, H., and Larson, E. (2004). "Socio-economic effect of studded tire use in Alaska." *Final Research Rep.*, Univ. of Alaska Anchorage, Alaska, ⟨http://soe.engr.uaa.alaska.edu/soe/Faculty/zubeck/final-socio-economic_effects_studded_tires_Alaska.pdf⟩.