DEVELOPMENT AND APPLICATION OF AUTOMATIC WINTER TIRE DISCRIMINATION DEVICE

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ABSTRACT

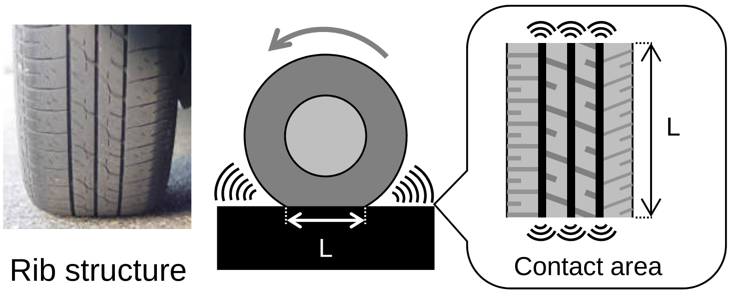
In Japan, winter tire use is mandatory on expressways in heavy snow regions during winter to ensure the safety and mobility of road users. Road operators need to check whether vehicles are equipped with winter tires. In the conventional inspection method, vehicles are stopped and the sidewall of tires are checked by personnel. However, traffic breakdown and a severe working environment could be problems. To solve these problems, the development of automatic winter tire discrimination device (AWTDD) was started. AWTDD discriminates winter tires from summer tires by analysing the frequency of noise caused by tires and the road surface, when vehicles are running with the time headway of 2 seconds or longer and at the speed of 35km/h or over. To verify the performance of AWTDD, several experiments were conducted. The results of on-road verification tests confirmed that AWTDD discriminates tires with an average accuracy of 75%. It was also found that AWTDD performance is largely affected by pavement conditions, and that road surface vibration is also a useful tool for tire type discrimination.
It is expected that AWTDD will be further improved to process as many as 1000 vehicles per hour.

1. INTRODUCTION

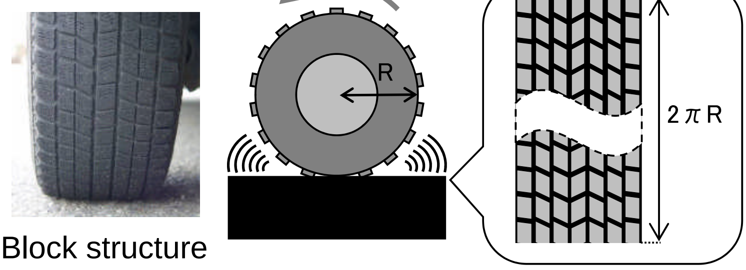
Expressway is indispensable for human life and logistics. Securing the safety and mobility of drivers on expressways is the principal responsibility of road operators. Especially in winter, road operators strive to ensure the safety of drivers and smooth flow of traffic by carrying out snow removal and de-icing operations. However, these operations may cause road or lane closures, which can cause an interruption of logistics services and profoundly affect economic activities. Winter tire regulation, under which vehicles without winter tires are stopped, is implemented as one measure to prevent such negative effects.

During winter tire seasons, vehicles are stopped and visually inspected for compliance with the winter tire regulation. The inspection process may cause two problems: traffic breakdown due to interrupted traffic flow, and heavy workload on personnel due to severe cold weather. Because of these problems, the improvement of efficiency of winter tire checking process, including the automation of the process, had been strongly required.

Against this background, NEXCO-Central started a collaborative research in 2010 with Central Nippon Highway Engineering Nagoya Company, Daido University and the University of Electro-Communications, aiming to develop the automatic tire type identification device. The conventional automatic tire type discrimination method, which is based on the image processing technology, has two problems: the cost of the device is quite high and the results tend to be affected by weather conditions. For these reasons, application of the conventional method was not further investigated.



a) Summer tire



b) Winter tire

Figure 1 - Structural differences between summer tires and winter tires

This caused the necessity of an alternative tire type discrimination method. For this new method, attention was focused on microphones because of their lower cost and non-contact feature. By using microphones, travelling sound of vehicle, which is generated between tires and the pavement surface, was collected for frequency analysis. The results of the analysis were used for basic discussion to investigate the new tire type discrimination method. Furthermore, experiments using the new device were conducted in January 2012 at the Nagaragawa Service Area, which is located on the Tokai Hokuriku Expressway managed by NEXCO-Central, in order to investigate the possibility of practical use of the new device. This paper reports on the status of the development of the new automatic tire type discrimination device.

2. CHARACTERISTICS OF TIRE NOISE

Figure 1 a) and 1 b) show a comparison of tread patterns between summer tires and winter tires. As shown in the figures, the biggest difference between two types of tires is that summer tires have continuous tread ribs, which increase straight-running stability and drainage capacity, while winter tires have independent tread blocks, which provide confident grip and traction on icy roads. The difference has been used in the conventional tire type discrimination method, which is done by reading tire sidewalls or observing tread patterns.

As for noise made by travelling vehicles, major components are engine noise, wind noise and tire noise which is caused by tires and the road surface. Tire noise is classified into the following three types.

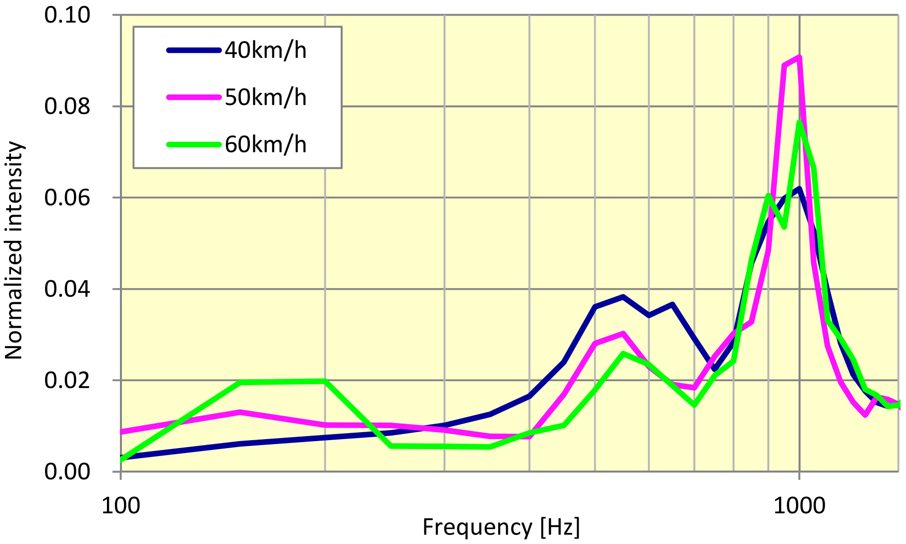
1) Pattern noise

Pattern noise occurs during vehicle operation when air is trapped in the tread pattern and then suddenly released as the tire rolls along the road surface. Since the values of pattern noise frequency are almost constant (around 1kHz for passenger vehicles), regardless of vehicle speed, pattern noise is often regarded as characteristic noise of summer tires.

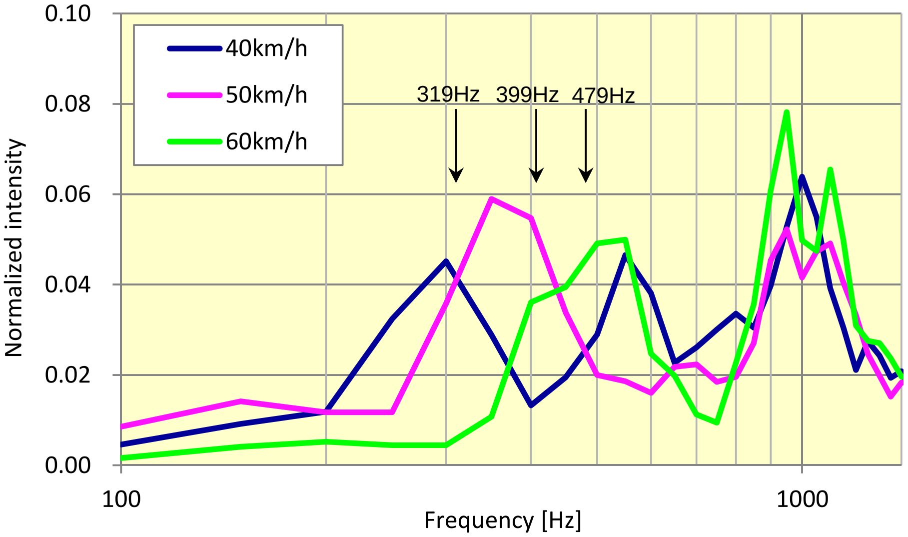
$$f = \frac{c}{2\left(L+\alpha\right)} \qquad \text{(Eq.1)}$$

Where, f is the resonance frequency of major tread groove (Hz), c is the speed of sound (m/s), L is the length of grooves contacting the road surface, and α is the correction coefficient for the open end.

2) Elastic vibration noise



a) Summer tire



b) Winter tire

Figure 2 - Normalized power spectra of tire/road noises

Elastic vibration noise is produced when independent tread blocks contact the road surface and the impact causes tires to vibrate. Elastic vibration noise is considered as characteristic noise of winter tires, and its frequency changes in proportion to the speed of vehicle.

$$f = \frac{V \cdot n}{3.6 \times 2\pi R} \qquad \text{(Eq.2)}$$

Where, f is the frequency of vibration (Hz), R is the radius of the tire (m), v is the speed of the vehicle (km/h), and n is the number of blocks.

3) Others

Other noise includes tire vibration noise caused by unevenness of the road, and air pumping noise caused by air pumped in and out of tire treads and road cavities.

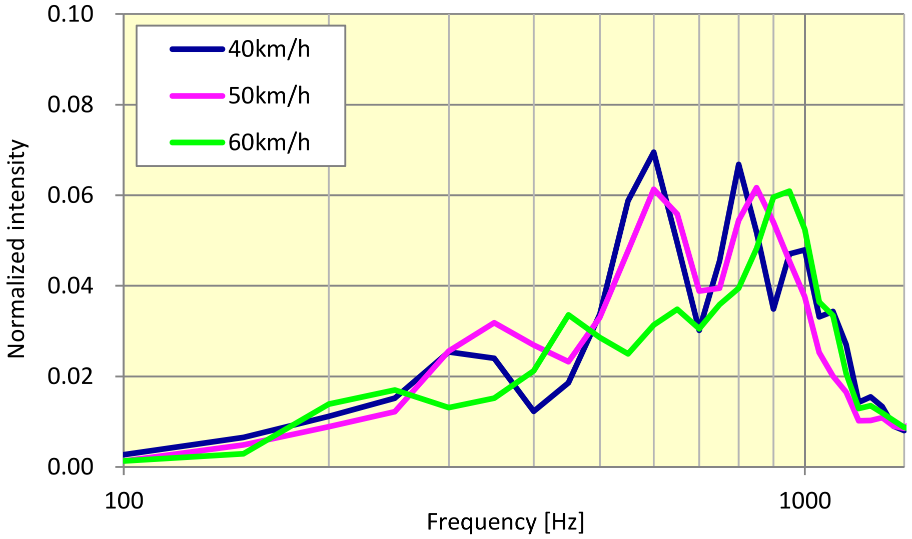
To confirm whether or not travelling noise can be used for tire type discrimination, an experiment was contacted at the Kanda Parking Area on the Hokuriku Expressway. In this experiment, microphones were placed at the rampway to the parking area and vehicles with summer tires or winter tires were run at different constant speeds: 40km/h, 50km/h and 60km/h. Figure 2 a) and 2 b) show the results of frequency analysis on the vehicle travelling sound data collected in this experiment. As it shows, summer tires' pattern noise frequency has its peak at around 1kHz, regardless of vehicle speed. In contrast, winter tires' peak values of frequency vary with vehicle speed, and these peak values, 319Hz at 40km/h, 399Hz at 50km/h and 479Hz at 60km/h, are close to the values calculated using Eq.2 above.

Based on the above, it was confirmed that characteristic noise is different depending on tread patterns. It was also confirmed that the types of tires can be identified by analysing the frequency of vehicle travelling sound.

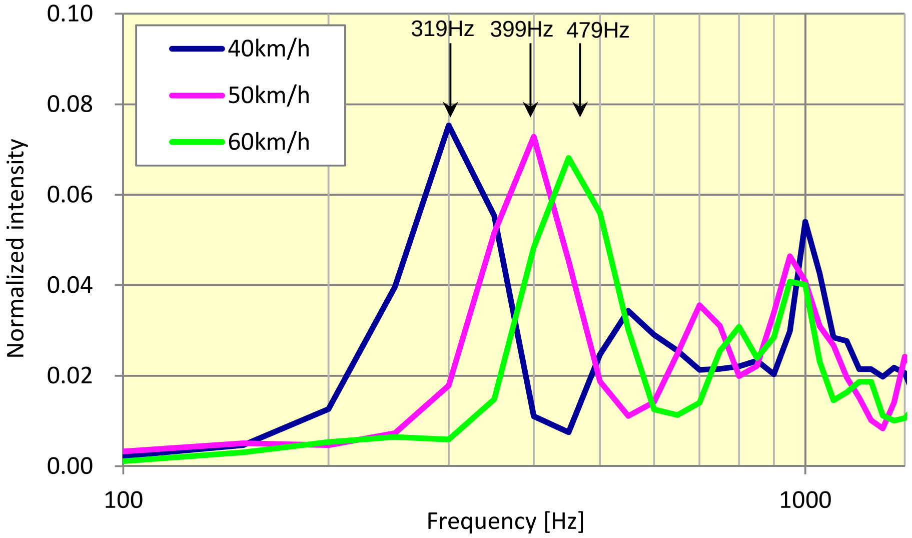
3. PAVEMENT SUITABLE FOR TIRE TYPE DISCRIMINATION

With regard to characteristic noise, which is the key factor in tire type discrimination, numerous tests were conducted at different locations. At the Kanda Parking Area on the Hokuriku Expressway, characteristic noise was extracted successfully as shown in Figure 2 a). In some places, however, characteristic noise was not obtained even though the pavement was similar with that of the Kanda Parking Area, a dense-graded asphalt concrete pavement. The main reason of such phenomena is unevenness of the road, as mentioned in (3) of Paragraph 2 “CHARACTERISTICS OF TIRE NOISE”. For stable tire type discrimination, it is necessary to remove the noise caused by unevenness of the road, so that characteristic noise can be extracted to the maximum extent. For that reason, the road with a fine-graded asphalt concrete pavement, which has lower surface roughness and enough skid resistance, is considered highly suitable for tire type discrimination.

To verify the effect of a fine-graded asphalt concrete pavement on tire type discrimination, a test road paved with fine-graded asphalt concrete was built in the work yard at the Gifu-Kakamigahara Interchange. The results of frequency analysis on winter tires with each type of pavement are shown in Figure 3 a) and 3 b). In Figure 3 a), the characteristic noise of winter tires did not appear when the vehicle ran on an aged road with dense-graded asphalt concrete, while winter tires' elastic vibration noise was clearly indicated when the vehicle ran on a road paved with fine-graded asphalt concrete.



a) Dense graded asphalt concrete



b) Fine graded asphalt concrete

Figure 3 - Effect of fine graded asphalt concrete

4. AUTOMATIC WINTER TIRE DISCRIMINATION DEVICE (AWTDD)

Figure 4 shows the component parts of the automatic winter tire discrimination device (AWTDD). It requires a microphone placed outside the road to collect vehicle travelling noise data, and a controller to analyse vehicle travelling noise and to identify the type of tires. In addition, vehicle detectors are installed every 5.5m to measure the passage timing and speed of vehicle and to identify the type of vehicle (heavy vehicle / passenger vehicle).

The flow chart of tire type discrimination process is shown in Figure 5.

AWTDD was installed for experiments at the entrance of the Nagaragawa Service Area on the Tokai-Hokuriku Expressway, where the road is paved with fine-graded asphalt concrete. These experiments were intended to compare discrimination accuracy between

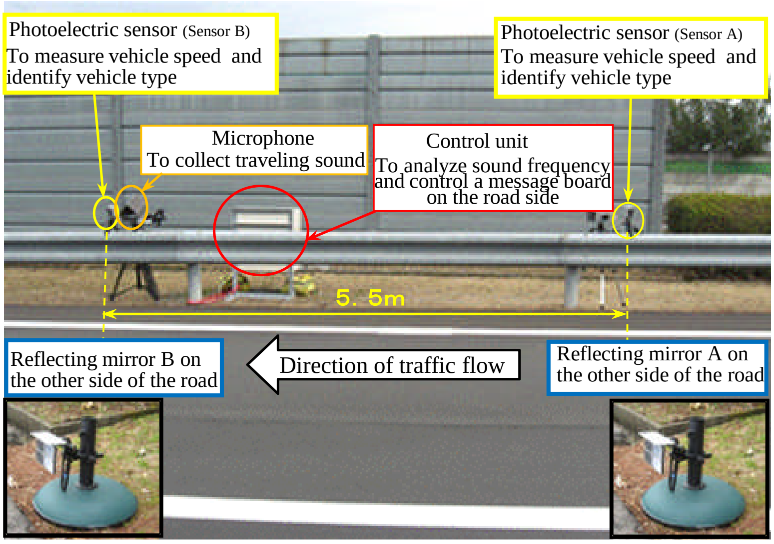


Figure 4 - Automatic tire discrimination device

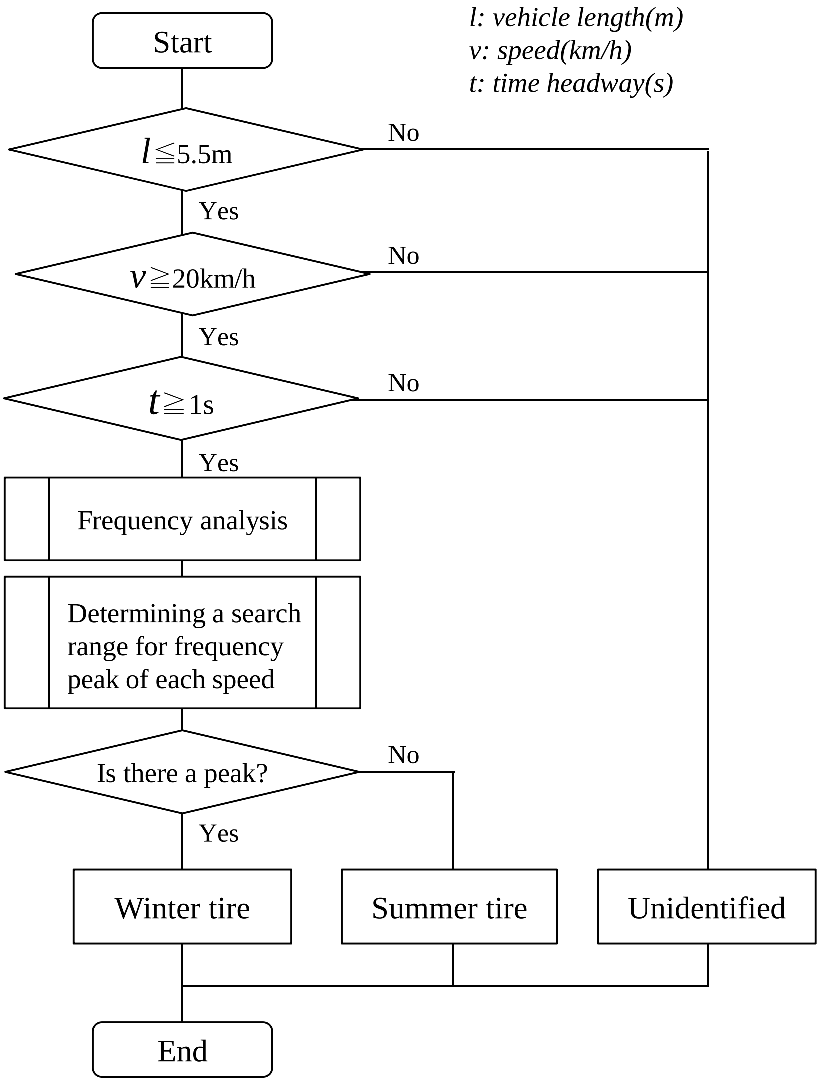
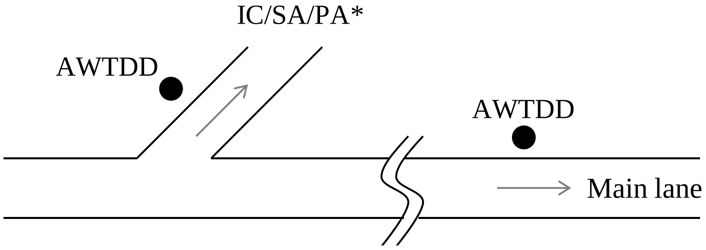


Figure 5 - Tire discrimination flow

AWTDD and visual checks by personnel. Four experiments were conducted in total, 2

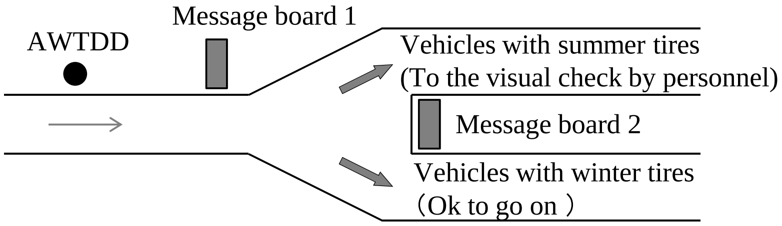
Table 1 - AWTDD accuracy examination

	Number of vehicles tested	Number of vehicles whose tires were identified correctly	Discrimination accuracy (%)
Vehicles with winter tires	1050	773	74
Vehicles with summer tires	1136	876	77
Total	2186	1649	75

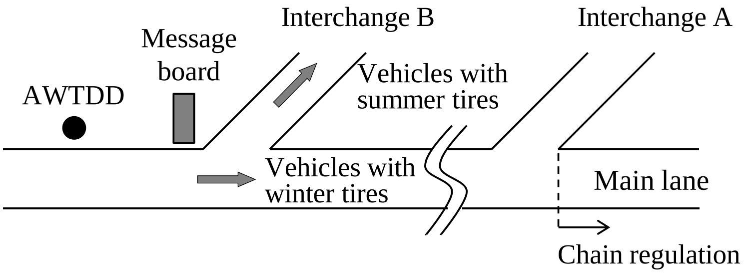


*: IC: interchange; SA: service area; PA: parking area

a) Winter tire use rate research



b) Pre-screening prior to the visual check by personnel



c) Directing non-winter tire vehicles to the exit

Figure 6 - Applications

times in December 2011 and once in March and April 2013 respectively, which are around the time to switch between winter tires and summer tires. Table 1 shows AWTDD accuracy data obtained in these experiments.

The vehicles tested were passenger vehicles, and traffic volume was about 2000veh/h. In these experiments, the accuracy of AWTDD was 75%, although the vehicles varied in types and sizes and were equipped with tires having different tread patterns. The results show, not only that a fine-graded asphalt concrete pavement is suitable for tire type discrimination by AWTDD, but that AWTDD is effective in identifying the type of tires.

5. APPLICATION

It is considered that AWTDD can be applied in the following three ways.

1) Winter tire use rate research

In some cases with high winter tire use rate, tire type checks by personnel can be omitted based on a decision by a road operator, even when the winter tire regulation is in place. To provide winter tire use rate needed for road operators to make such decisions, AWTDD can be placed at the ramp of interchange or rest area, or on the mainline as shown in Figure 6 a).

2) Pre-screening prior to the visual check by personnel

When winter tire regulation is in place, AWTDD can be used to direct the traffic into two lines: those with summer tires and those with winter tires, as shown in Figure 6 b). The results of AWTDD are displayed on variable message boards. This allows vehicles with winter tires to continue their travel without stopping for a visual check by personnel. It will not only relieve traffic congestion and reduce the workload on personnel, but also contribute to less CO_2 emission by avoiding unnecessary stopping and starting of traffic.

3) Directing non-winter tire vehicles to the exit

As shown in Figure 6 c), AWTDD and a variable message board can be placed at the upstream of the winter tire regulation section to direct non-winter tire vehicles to the exit. It is also possible to place AWTDD at the entrance of interchanges to remind drivers to install winter tires before entering the main line.

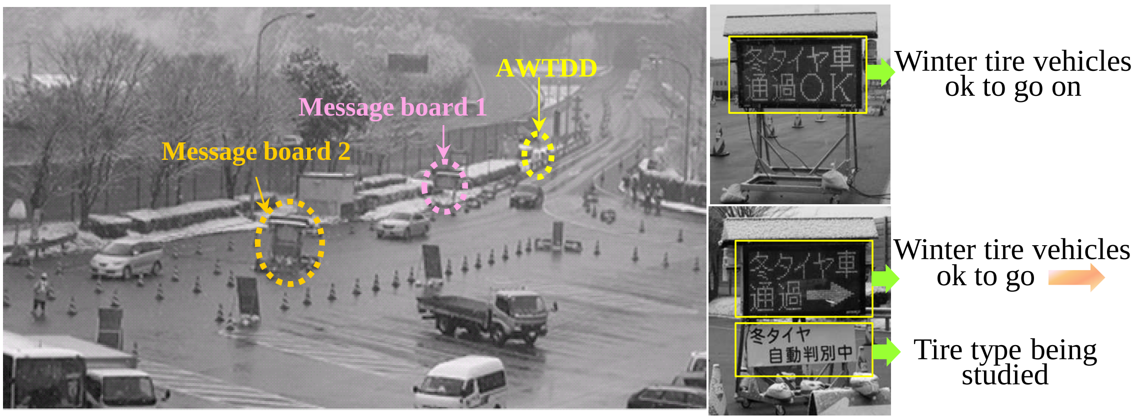


Figure 7 - Application of the automatic tire discrimination device

Figure 8 – Constant flow of vehicles

6. TEST OPERATION DURING WINTER TIRE REGULATION PERIODS

In January, 2012, AWTDD was introduced on a trial basis at the Nagaragawa Service Area on the Tokai-Hokuriku Expressway, while winter tire regulation was in place. In the conventional manual tire type discrimination method, all vehicles on the mainline are directed to the rest area for winter tire use checks by personnel. In this experiment with AWTDD, variable message boards on the entrance ramp of the rest area directed traffic into two lines, as shown in Figure 7. Vehicles with winter tires, including heavy vehicles, were directed to the route on the right, while vehicles with non-winter tires and those with unidentified tires were directed to go via the route on the left.

In this experiment, the following two conditions were used.

1) Time headway of 2 seconds or longer

If the time headway between vehicles is too small, AWTDD results may be transmitted incorrectly and the noise made by preceding and following vehicles may affect the results. For such reason, a headway of 2 seconds or longer was chosen for this experiment.

2) Vehicle speed of 35km/h or over

Vehicle speed was set at 35km/h or over, since it is difficult to extract characteristic noise when vehicles travel at a low speed.

In this experiment, AWTDD functioned successfully when traffic volume was low. With the increase of traffic, however, time headways of vehicles sometimes became shorter due to 1km-long closure of passing lane, resulting in a constant flow of vehicles, as shown in Figure 8. This caused many vehicles to fail to satisfy the test conditions, time headway of 2 seconds and speed of 35km/h, and these vehicles were detected as having “unidentified tires”.

7. ROAD SURFACE VIBRATION CAUSED BY VEHICLES

In the experiment mentioned above, AWTDD accuracy was around 75%. According to maintenance personnel in charge of winter tire use checks, however, the accuracy still needed to be improved. One problem was that some vehicles travelled at a relatively low speed with a short time headway, because, with such driving conditions, vehicle tires were not identified by AWTDD. The number of such vehicles tended to increase as traffic volume increased. Another problem was that noise produced by vehicles around the subject vehicle had a negative effect on the accuracy of AWTDD.

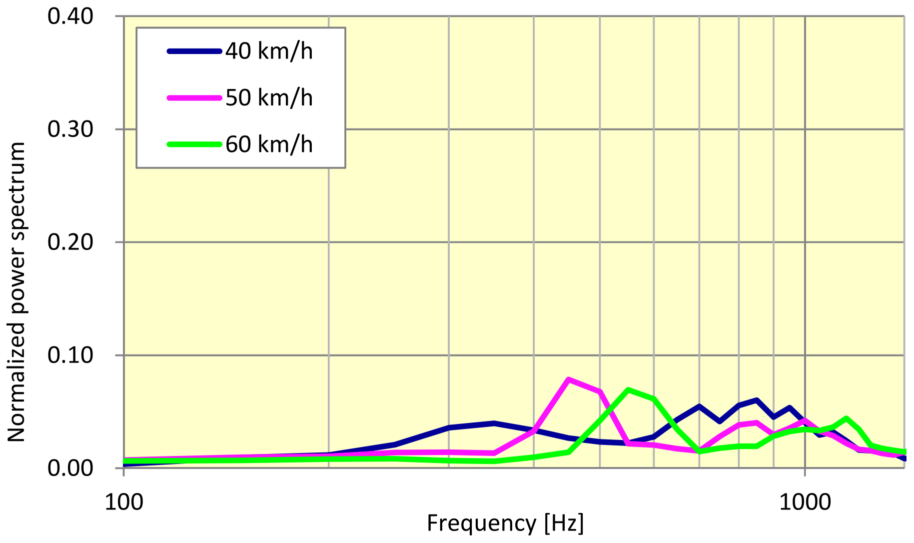
For the latter problem, an assumption was made that such noise includes not only airborne noise but also the vibration of road surface caused by tread pattern unique to winter tires. Based on this assumption, we reasoned that the types of tires on slow-moving vehicles can be successfully identified if road surface vibration data is available. In this way, the effect of noise caused by other vehicles also can be eliminated. It is also expected that it would reduce the influences of winds and other meteorological factors on the results.

Figure 9 shows the results of the experiment conducted on the test road at Gifu-Kakamigahara Interchange. The results showed that the wave profile of vehicle vibration is more distinctive than that of vehicle sound, indicating that the wave profile of vibration is a useful tool for detecting winter tires. Furthermore, it was found, by confirming positional relation between tires and the vibration measuring machine, that road surface vibration is largely attenuated with distance. This can be seen in Figure 10, which shows waves of front tires and rear tires appearing separately.

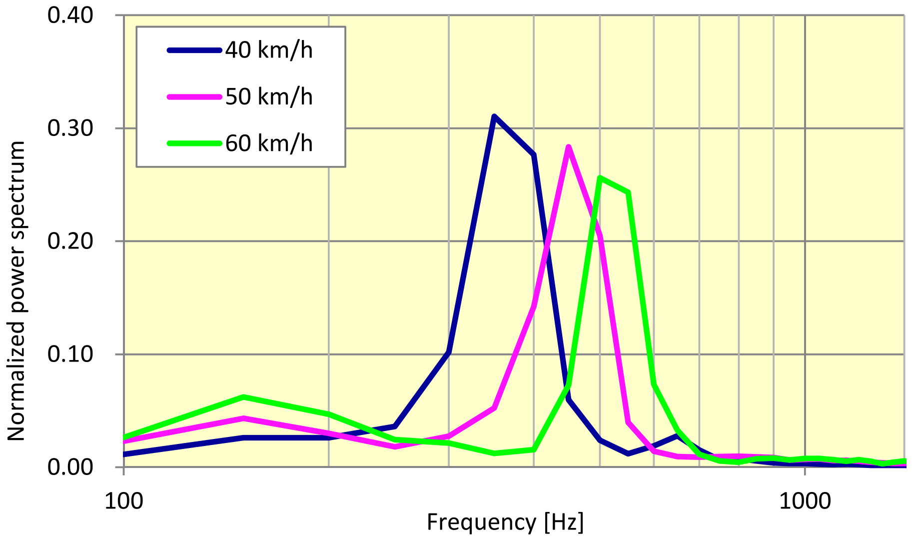
In September 2012, on the test road located at the Shirotori Interchange on the Tokai-Hokuriku Expressway, vehicles with summer tires and those with winter tires were run at different speeds to compare accuracy between tire type discrimination by vibration measurement and discrimination by sound measurement. Discrimination accuracy of each test method is shown in Figure 11.

Table 2 summarizes test conditions for both test methods. Tire type discrimination by sound measurement can be put into practical use if the conditions are relaxed, although this should slightly reduce discrimination accuracy.

During the period from December 2012 to February 2013, AWTDD was used at 10 sites on expressways managed by the Nagoya branch of NEXCO-Central.



a) Sound frequency analysis

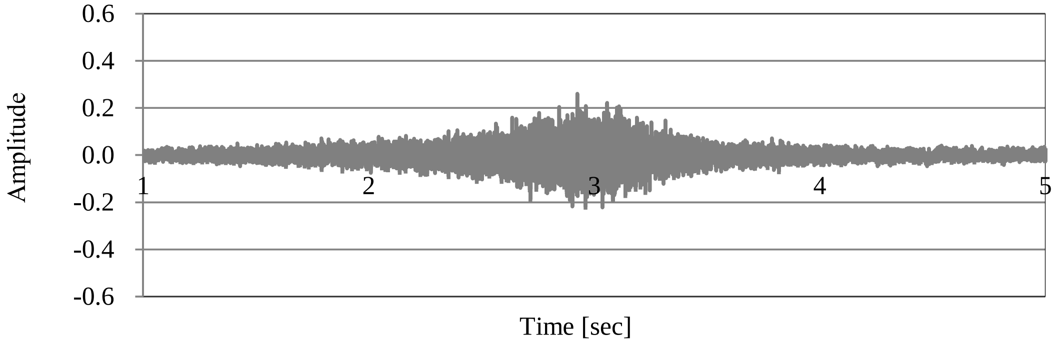


b) Vibration frequency analysis

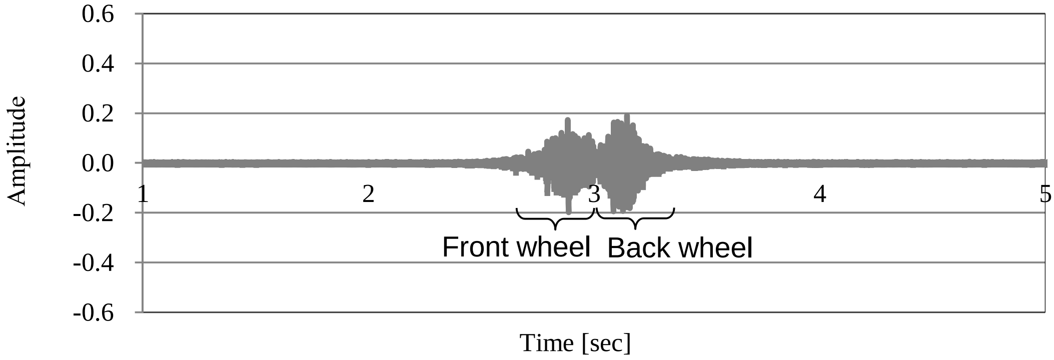
Figure 9 - Frequency of sound and vibration for each speed

Table 2 - Test conditions for each test method

	Discrimination by sound measurement	Discrimination by vibration measurement
Pavement condition	Small roughness	
Vehicle type	Passenger car (vehicle length of 5.5m or less)	
Road surface condition	Dry, wet, muddy snow	
Vehicle speed	30km/h or more	20km/h or more
Time headway	1.5 seconds or longer	1.0 second or longer
Discrimination accuracy	75%	85%



a) Sound amplitude



b) Vibration amplitude

Figure 10 – Wave patterns of sound and vibration amplitude over time

The operation of AWTDD is significantly affected by the condition of pavement. In our experiments, we confirmed that characteristic noise and vibration of tires are successfully extracted regardless of whether the road is paved with fine-graded asphalt concrete or dense-graded asphalt concrete.

8. CONCLUSION

NEXCO-Central has been working on the development of automatic winter tire discrimination device (AWTDD) since the winter of 2010, aiming to improve the efficiency of winter tire use checking process, and to realize the automation of the process. Based on the results of verification tests, we have confirmed that AWTDD successfully identifies the type of tires. It is expected that AWTDD will be further improved to process as many as 1000 vehicles per hour in the near future.

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