# A Speed Restraint Pavement with a Longitudinal Surface Profile of Sine Waves

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ABSTRACT: Although the speed limits for the streets in residential areas are generally set to secure the safety of pedestrians and restrain the traffic noise, they are often violated. The speed bump is a method of pavement technology that forces traffic to go slowly. However it is not appropriate to apply it to ordinary roadways, because over a certain speed it will have adverse effects such as a shock to the driver and damage to the body or the cargo. In addition, the braking and the accelerating to pass over the speed bump will generate more traffic noise. "Speedsave" is an innovative speed restraint pavement with a longitudinal surface profile of sine waves. Its longitudinal surface profile which is the height and the length of the waves, is designed according to the given speed limit of the road. While a vehicle passing over the pavement at speeds under the limit can drive over it without any trouble, a vehicle moving at a speed over the limit will feel the resonance of its suspension and the driver will start to feel bad thus making him lower his vehicle speed. In the paper, we describe the details of Speedsave, including surface profile design, paving machines and processes, and we look at one example of its application on a typical residential street and the results.

KEY WORDS: Bump, wave, pavement, sine, speed.

## 1. Introduction

In all countries, roadway is demanded to be safe, comfortable and environmentally-friendly. Particularly roads must be safe as it is the most fundamental concept in roadway design. However, increases in traffic accidents, noise, vibration and air pollution caused by traveling vehicles are still social issues. Driving within speed limit is an essential road manner, but violation of the speed regulations has never ceased partly due to improved performances of vehicles, and the number of traffic accidents has not decreased.

An effective measure for reducing traffic accidents is controlling the speed of vehicles, and various attempts have been made in many countries. Implemented methods include "chicane", which involves constructing road alignment that forces vehicles to make repetitive short turns, "narrowing", which involves narrowing the road width at a part of the road, and "speed bumps", which involves forming protuberances on the road surface. Of these, "chicane" and "narrowing" have been effective in community roads in residential and commercial districts but are difficult to use for highways where heavy vehicles pass.

Speed bumps, which have circular or trapezoidal cross sections, restrain speeding by giving unpleasant shocks to drivers while passing over but may endanger driving, cause jolt cargo, damage the vehicles and/or cargo, and increase noise and vibration. Thus, speed bumps can only be installed on community roads and other limited road sections in practice.

The authors developed speed restraining pavement that has the advantages of speed bumps and is feasible for ordinary roadways by eliminating their disadvantages. This paper summarizes the development history of the technology, design and construction methods and the results of their on-road application of these.

## 2. OVERVIEW OF DEVELOPED PAVEMENT (SPEEDSAVE)

A conceptual diagram of the pavement developed for restraining speeding (hereinafter referred to as “Speedsave”) is shown in Figure 1. Speedsave has a longitudinal surface profile consisting of at least 3 continuous smooth sine waves. The waved surface causes resonance to vehicles that travel faster than a certain speed, and the jolting gives the drivers an unpleasant driving experience and encourages them to slow down.

Speedsave also ensures safe and continuous driving of vehicles traveling within the speed limit (at the legally permitted speed). The surface, which has a sine wave profile, is also designed so as not to endanger vehicles traveling faster than the speed limit and not cause noise, vibration, or other problems caused by ordinary speed bumps.

The longitudinal profile of Speedsave is shown in Figure 2. Compared to conventional speed bumps, the longitudinal length is as long as 3 sine waves extended over 20 to 60 m (the length varies depending on the design speed). The height of the waves is about 60 mm from the driving road surface.

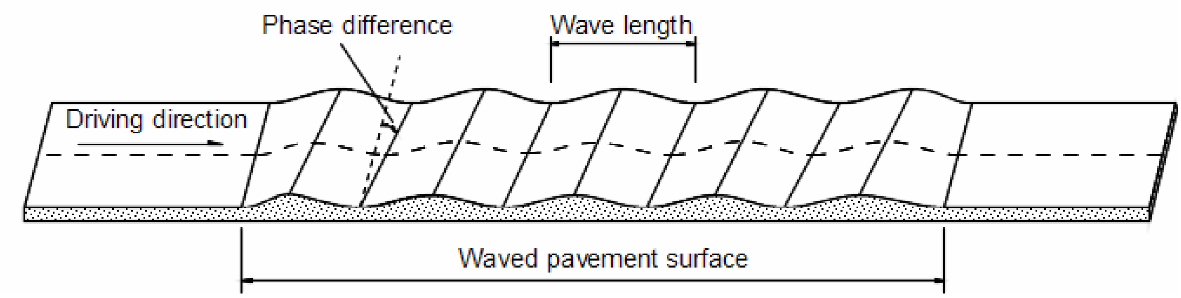


Figure 1: Conceptual diagram of Speedsave

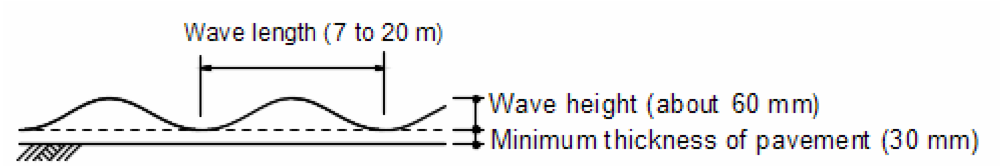


Figure 2: Example of Longitudinal profile of Speedsave

## 3. HISTORY OF DEVELOPMENT

### 3.1 Investigation of Rectangular Speed Bumps

In 1995, a group’s (of hot rodders) repeated reckless driving in a commercial park in Omiya, in southern Saitama Prefecture raised complaints about noise from local citizens. We investigated various control measures together with the police and municipal office and installed rectangular bumps to restrain the speed of vehicles and motorcycles (Figure 3).

The bumps stopped reckless driving, but caused unintended problems, such as vibration and load collapse on trucks during their passage through the park.

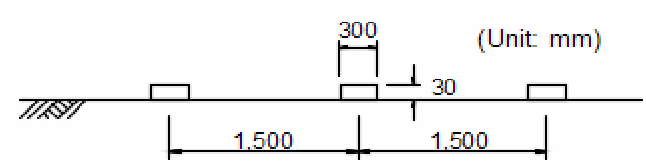


Figure 3: Profile of rectangular bumps

## 3.2 Investigation of Speed Bumps That Give Little Shocks to Slow Traveling Vehicles

As hot rodders returned to newly constructed roads in the park, new profiles of speed bumps were investigated aiming to also solve the problems of the rectangular bumps. The goals were to ensure the comfort of driving at speeds slower than about 30 km/h and to give drivers and riders an unpleasant ride at high speeds.

Instead of rectangular speed bumps, continuous circular arc bumps (longitudinal distance: 5 m, height 10 cm) and continuous sine wave bumps (wavelength: 5 m, wave height: 7 cm) with further reduced shocks were constructed (Figure 4). The new speed bumps eliminated the hot rodders but were still a discomfort even at 30 km/h. Thus, the configuration was further investigated.

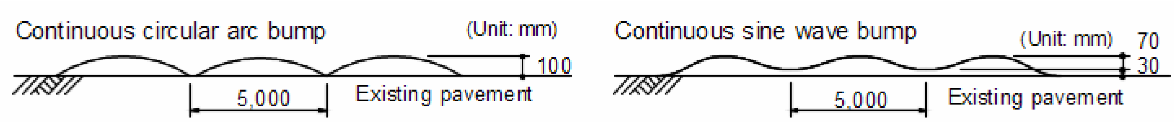


Figure 4: Continuous circular arc bumps and continuous sine wave bumps

## 3.3 Development of Speedsave

(1) Development of waved surface

In order to eliminate the disadvantages while keeping the advantages of speed bumps, the new pavement was to be developed based on the following principles:

1) The profile of road surface was to be sine waves in principle, which enables smooth passage of vehicles.

2) The wave height and wavelength were to be those that allow smooth driving at speed limits or legally permitted speeds and make unpleasant to drive at speeds exceeding the limit by 20 to 30 km/h.

3) At least 3 waves were to be repeated in succession to give both resonance and oscillation to vehicles traveling at high speeds to enhance the speed restraining effects.

4) To amplify the unpleasant feeling, phase difference was to be established between the right and left wheels of the axle to force the vehicle to roll side to side.

This was decided because ordinary sine waves cause vehicles to only pitch front to back while sine waves with phase difference make the vehicles roll as well (Figure 5).

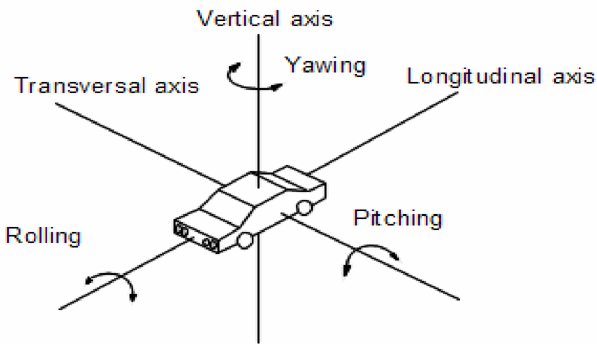


Figure 5: Movements of traveling vehicle

Based on the principles we adopted, the best sine waves of the road surface were to be determined by 1) calculating the vibration acceleration from the front and rear wheel loads, spring constant, other specifications of vehicles, and the amplitude, wavelength and phase angle of the bumps, and 2) superimposing the results with the vibration sensation curve of Meister, which shows the relationship between vibration acceleration and human perception of vibration.

In 1995, a test course was constructed in the yard of our facility, and tests were conducted to assess the effectiveness of the new pavement, workability, and resultant surface profile.

Aiming to allow pleasant driving at 30 km/h and make driving at 60 km/h unpleasant, the road surface was to have the configuration shown in Table 1 (Surface 1). Three waves (length: 21 m) of Surface 1, and three waves (length: 21 m) of Surface 2 which had a reduced wave height of 30 mm for comparison, were constructed.

Table 1: Specifications of surfaces tested

| Surface No. | Profile | Wavelength (m) | Wave height (mm) | Phase difference(degrees) |
|---|---|---|---|---|
| 1 | 3 sine waves | 7 | 50 | 20 |
| 2 | 3 sine waves | 7 | 30 | 20 |

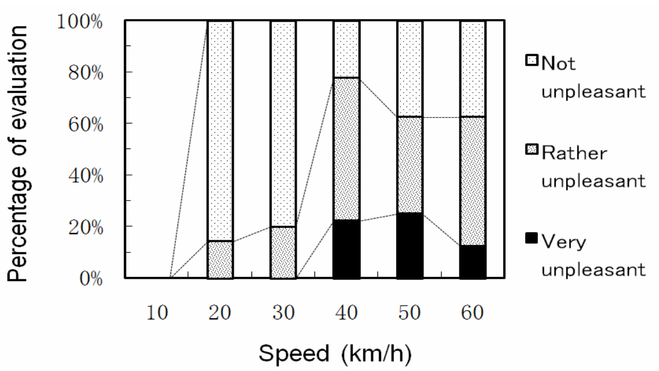



Figure 6: Unpleasantness of driving the test course

The effects were assessed by 10 drivers, including 2 policemen, who drove at 20 to 60 km/h and evaluated the unpleasantness of driving at each speed level in 3 grades. On Surface 2, no drivers mentioned unpleasantness. The reactions of the drivers to Surface 1 are shown in Figure 6. Up to a traveling speed of 30 km/h, almost no driver felt unpleasant, and the majority of the drivers felt unpleasant driving at or over 40 km/h.

(2) Investigation of construction method

Conventional paving machines cannot construct the correct surface profile consisting of sine waves with phase difference. Thus, a special asphalt paver and a special pneumatic tire roller developed for constructing special test courses for automobile tests were used, and their applicability was evaluated. The characteristics of the paving machines and the construction method are described below.

1) Special asphalt paver

The main part of the paving machine is no different from conventional asphalt finishers. Uniqueness is seen in its screed, which is supported by vertically extendable outriggers. The screed board is divided into 11, and each is computer controlled in order to pave the road so as to have the predetermined profile (Photo 1(A)).

To control deformations of waveform during rolling compaction, double tampers were used for compaction. To ensure high degree of compaction of at least 90% immediately after the spread of asphalt concrete, the execution speed was 1 m/min.

2) Special pneumatic tire roller and rolling compaction

When there is phase difference, both the longitudinal and transversal profiles of Speedsave are curved. Thus, conventional rollers cannot be used as they would deform the waveforms. A special pneumatic tire roller (Photo 1(B)) that can compact the surface in accordance with the surface profile is needed. The special pneumatic tire roller consisted of 3 front and 4 rear tires, each of which moved vertically and independently so as to fit the waves and always touched the pavement. The rolling compaction after spreading was executed 4 times at a speed of 10 m/min.


A: Special asphalt paver B: Special pneumatic tire roller

Photo 1: Paving machines

The results of constructing the sine waved road surface to the predetermined specifications (Table 1) using the paving machines are shown in Figure 7. The figure compares the design and measured values. It shows that the difference in wavelength was small and the difference between the design and formed wave height was only several millimeters and was negligible. Therefore, the machines were found to be feasible, and Speedsave was demonstrated to be constructed by the same number of workers as for ordinary asphalt pavement using the same procedure.

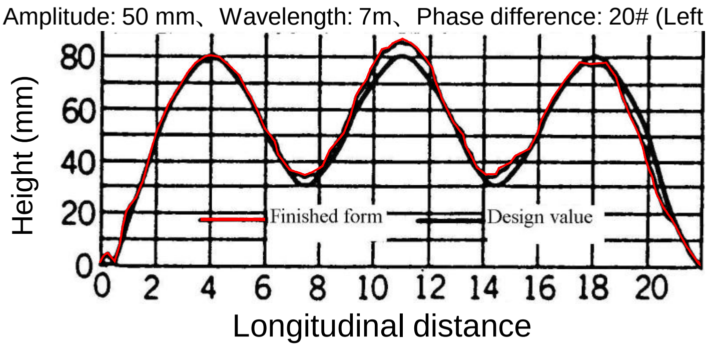



Figure 7: Finishing shape of waved surface

## 4. ESTABLISHMENT OF DESIGN METHOD

### 4.1 Overview of Investigation

Investigations described above qualitatively showed the effectiveness of Speedsave in restraining speeding. To establish the design method of Speedsave, waved road surface sections were constructed on a test course of Japan Automobile Research Institute, Inc. (JARI). The behaviors of vehicles on the waved surface were monitored, and sensory evaluation by ordinary drivers was conducted. The relationship between vehicle behavior and sensory evaluation was investigated aiming to find the universal criteria for designing road surface profile of Speedsave.

The specifications of the test road surfaces are shown in Table 2. The waveforms were all sine waves, and the 4 surfaces differed in wave height and phase difference. The surfaces were constructed using the method described in Section 3.3(2) and ordinary dense graded hot mixed asphalt.

Table 2: Specifications of test road surfaces

| Surface No. | Profile | Wavelength (m) | Wave height (mm) | Phase difference (degrees) |
|---|---|---|---|---|
| 1 | 4 sine waves | 20 | 30 | 40 |
| 2 | 4 sine waves | 20 | 50 | 0 |
| 3 | 4 sine waves | 20 | 50 | 40 |
| 4 | 4 sine waves | 20 | 70 | 0 |

4.2 Testing Methods

(1) Behaviors of vehicles

Acceleration was measured by installing strain gauge type accelerometers at 9 points, such as under the driver's seat and at wheels. Pitch and roll angles and speeds were monitored using a rate gyro installed near the center of gravity of the test vehicle.

The vehicle used for the test was an ordinary passenger car (sedan, 2000 cc class). Driving speeds were 60, 80, 100 and 120 km/h.

(2) Sensory evaluation

Sensory evaluation was conducted by 13 male drivers of 25 to 40 years. The unpleasantness of driving was expressed in scores of 5 grades shown in Table 3.

Table 3: Scores of unpleasantness

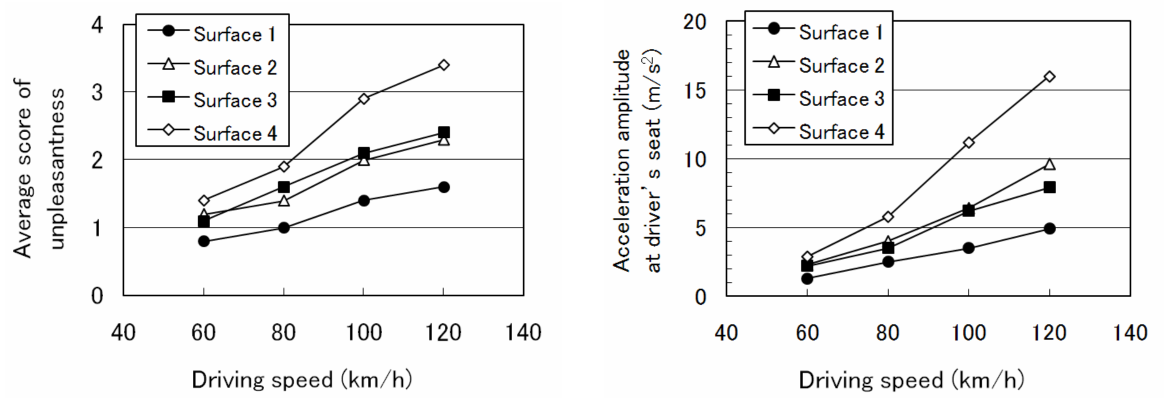
| Score | Evaluation of unpleasantness |
|---|---|
| 0 | Not unpleasant |
| 1 | Slightly unpleasant but negligible |
| 2 | Unpleasant but acceptable |
| 3 | Quite unpleasant |
| 4 | Very unpleasant |

4.3 Results of the Tests

The coefficients of correlation were calculated between the monitored values and sensory evaluation scores. Unpleasantness was found to be most closely correlated with acceleration amplitude monitored under the driver's seat (hereinafter referred to as "acceleration amplitude at driver's seat") with the coefficient of correlation of 0.97. Therefore, acceleration amplitude at driver's seat was decided to be treated as a factor that directly affects the scores of sensory evaluation. As the scores of sensory evaluation varied greatly depending on driver, the average of all drivers' scores was used.

The relationship between the driving speed and the score of sensory evaluation (Unpleasantness) is shown in Figure 8(A), and the relationship between the driving speed and acceleration amplitude (Acceleration amplitude) is shown in Figure 8(B). The score of unpleasantness and acceleration amplitude at driver's seat increased along with an increase in driving speed and also for higher wave heights. A comparison between Surfaces 2 and 3, which had the same wave height and differed in phase difference, showed that the acceleration amplitude was slightly smaller on Surface 3, which had phase difference, than on Surface 2, but the score of unpleasantness was higher on Surface 3. The phase difference reduced pitching but increased unpleasantness by increased rolling, and was shown to be effective (Figure 5).

From the results, the relationship between acceleration amplitude and unpleasantness was summarized (Figure 9). An acceleration amplitude of 7 m/sec$^2$ or larger was found to be unpleasant to drive, which can be used for designing the surface configuration of Speedsave.




A: Unpleasantness B: Acceleration amplitude

Figure 8: Relationship between driving speed and unpleasantness, acceleration amplitude

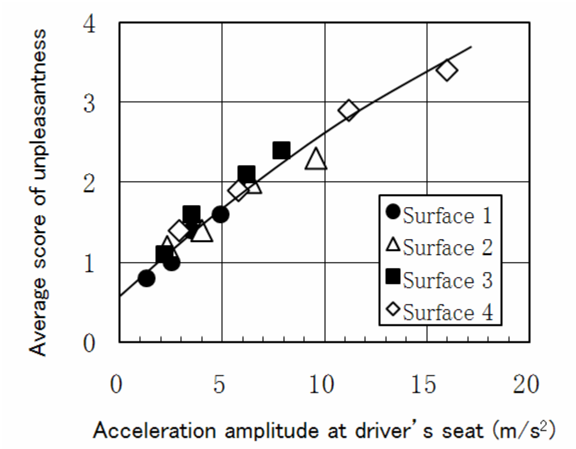



Figure 9: Relationship between acceleration amplitude and unpleasantness

4.4 Flow of Design

Based on the test results at JARI, a standardized design method was developed. A simplified design flow is given below:

1) Surveying the road states

The road section at which Speedsave is to be installed is to be carefully surveyed for road alignment, actual traveling speeds, traffic volume, passage of heavy vehicles, distance between intersections, legally permitted speed, etc.

2) Setting speed conditions

The speed that is not unpleasant to drive (hereinafter referred to as the “restraint speed”) and speed (“excess speed”) that is 20 km to 30 km faster than the restraint speed are to be decided based on the road survey results. The restraint speed is commonly the legally permitted speed.

3) Investigating pitching

Wavelength is to be determined so that the pitching of a vehicle traveling at the excess speed is 1 to 2 Hz. This is because the resonance frequency of the spring weight of an ordinary vehicle is about 1.5 Hz.

Wave height is to be determined using the experimental equation developed at JARI so that the acceleration amplitude at driver's seat a ($m/sec^2$) on the waved surface is $a < 7$ at or under the restraint speed and $12 < a < 15$ at the excess speed. The wave should be checked to not be excessively high by calculating the vertical displacements at the driver's seat.

4) Investigating rolling and correcting wave height

After deciding the phase difference, rolling is to be assessed using the experimental equation. As phase difference reduces pitching of vehicles, the wave height is to be corrected depending on the phase difference.

## 5. APPLICATION ON ROADS IN SERVICE AND EVALUATION

### 5.1 Overview of Application

Speedsave has been constructed on about 100 road sections since its first full-scale application in 1996 as a measure to control speed, ensure safety and reduce noise on community roads in residential districts, highways in industrial parks, and mountain roads, etc. At all sites, the pavement has been highly evaluated. Three representative cases are described in this section (Table 4).

Table 4: Overview of the works

| | | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|
| Year of construction | | 1998 | 2001 | 2009 |
| Site | | Highway by a housing complex | Mountain road | Community road in a residential district |
| Objectives | | Control speed and noise | Eliminate reckless driving | Reduce traffic accidents |
| Width, Area | | 8m, 914 ㎡ | 7.5m, 3,070 ㎡ | 6m, 320 ㎡ |
| Speed conditions | Restraint speed (legally permitted speed) | 30km/h | 40km/h | 35km/h |
| | Excess speed | 50km/h | 60km/h | 55km/h |
| Surface profile | Wavelength, Wave height, Phase difference | 11m,70mm,20 ° | 10m,55mm,20 ° | 10m,60mm,20 ° |
| | Number of waves | 5 (2 series) | 4 (3 series ), 5 (5) | 5 (1 series) |
| Other | | Dense graded asphalt concrete with PMB (Protrusions painted) | Dense graded asphalt concrete with PMB (Trick art at the starting point) | Dense graded asphalt concrete with PMB (Colored mixture) |

### 5.2 Controlling Speed

Case 1 was on a highway that passes through a large housing complex in Shinagawa Ward, Tokyo. The site was open and straight for about 800 m and was adjacent to the complex. The percentage of heavy vehicles was as high as 20 to 30%, and the traffic volume was as large as about 5,000 vehicles per day in each direction.

The speeds of traveling vehicles were measured before and 16 days after the construction of Speedsave using photoelectric speed meters. The results are shown in Figure 10. The pavement reduced the mean speed by about 7 km/h and the 85 percentile speed by about 9 km/h (from 60.3 km/h before execution to 51.7 km/h after execution). As shown in the plot, the number of vehicles traveling at 60 km/h or over was sharply reduced. The speed reduction was estimated to reduce noise by 1 to 2 dB. No changes in traffic volume were observed before and after execution. A view of the highway after execution is shown in Photo 2(A).

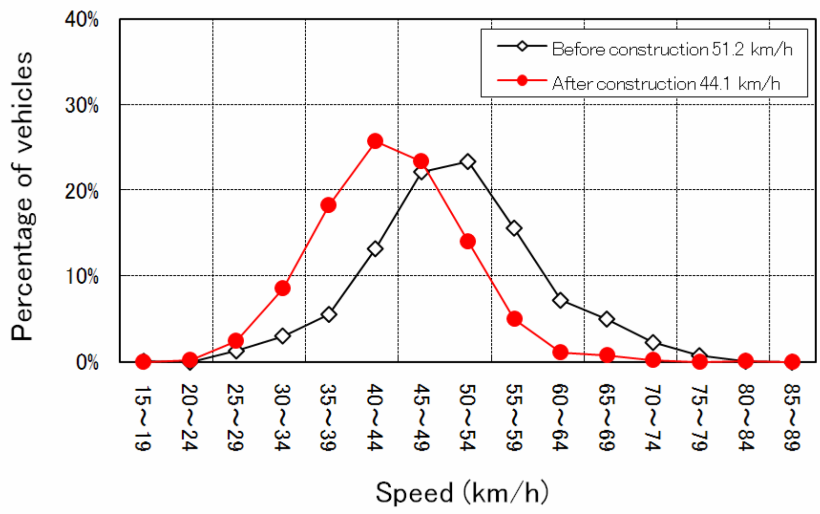


Figure 10: Vehicle speed distribution before and after the construction of Speedsave

5.3 Eliminating Reckless Driving

Case 2 (Photo 2(B)) was executed in Akagiyama, Gunma Prefecture, in 2001 aiming to eliminate reckless driving, such as making unnecessary drifting and weaving. The pavement has been reported to eliminate reckless driving. Speedsave has been constructed to eliminate reckless driving in 35 sections and has been also effective against drag racing on linear roads and dangerous driving by two or more vehicles or motorbikes.

5.4 Reducing Traffic Accidents

Case 3 (Photo 2(C)) was executed in 2009 on a community road in Ayase City, Kanagawa Prefecture, aiming to reduce traffic accidents and noise. Vehicles passed through the narrow road of only about 6 m in width at high speeds and caused frequent accidents near intersections. As a control measure, Speedsave was constructed on a part of the road. Because it is still new, there is no concrete data on the effect. In another case, which was executed in 1997 for a similar objective, the number of traffic accidents in a year was reduced from 7 to zero by the construction of Speedsave.

Also on a mountain road in Nagasaki, Speedsave has reduced traffic accidents from 16 to 1 in a half year span.


A: Housing complex B: Mountain road C: Residential district

Photo 2: Application case

## 6. SUMMARY AND FUTURE TOPICS

Speedsave, which aims for traffic safety by restraining speeding, has eliminated the disadvantages of speed bumps and is feasible also for highways. Compared to ordinary speed bumps, Speedsave has the following advantages:

1) Within the speed limit, vehicles can travel smoothly,
2) Speeding can be restrained over a long section,
3) It is feasible also for highways with heavy vehicle traffic by using the appropriate wavelength and wave height,
4) Noise and vibration can be reduced by the waved road surface, and
5) Bicycles and motorbikes can travel safely.

With these advantages, Speedsave has been widely implemented on the following sections for the purposes described below:

1) Controlling speed in residential districts (reduce traffic accidents, noise and vibration),
2) Eliminating reckless and dangerous driving on mountain roads (against weaving),
3) Eliminating reckless and dangerous driving on roads in industrial parks (against drag racers), and
4) Eliminating dangerous driving on linear roads (against drag racers).

A problem is that Speedsave is difficult for drivers to perceive as the surface looks smooth. Vehicles running at a speed largely exceeding the speed limit and illegally converted cars (hot rods) may collide against the pavement or lose control when the drivers fail to detect the waved surfaces. To ensure safety of such eventualities as well as of others, all bumpy surface zones are marked with road markings and installed with warning posts to warn drivers, but the warning may be insufficient.

Therefore, a comprehensive system is needed to encourage all drivers, including those who are strangers to the site, to decelerate before entering into the zones by informing them to perceive the zones, such as by coloring the road surface and installing standardized road markings prior to entering the zones.

Based on our experiences, it is essential to obtain the understanding and cooperation of nearby residents and work in cooperation with the police and road managers for construction of Speedsave.

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