Development of the Effective Voice Warning for Drivers at Open Section

Kouji Yamamoto 1, Hideki Takahashi 2[1], Takashi Yamanoto 3, Hideki Yazawa 4

Tokyo Branch, Central Nippon Expressway Co., Ltd.,
4-3-1 Toranomon, Minato-ku, Tokyo, Japan, Email; k.yamamoto.af@c-nexco.co.jp (of author 1)
Corporate Strategy Dept., Central Nippon Highway Engineering Nagoya Co., Ltd.,
1-8-11 Nishiki, Naka-ku, Nagoya, Japan, Email; h.takahashi.a@c-nexco-hen.jp (of Author 2)
Maintenance Strategy Headquarters, Central Nippon Expressway Co., Ltd.,
2-18-19 Nishiki, Naka-ku, Nagoya, Japan, Email; t.yamamoto.ae@c-nexco.co.jp (of Author 3)
Facility Engineering Dept., Central Nippon Highway Engineering Tokyo Co., Ltd.,
1-23-7 Nishi-Shinjuku, Shinjuku-ku, Tokyo, Japan, Email; h.yazawa.aa@c-nexco-het.jp (of Author 4)

Abstract

The present traffic safety measures appeal to the eyes, then they are not fully effective in some cases, like for a driver without looking ahead, a hazy driver and so on. Audible warnings, on the other hand, allow the driver to hear the warning unconsciously and easily understand its meaning. For this reason, the auditory system can become the effective traffic safety measures because it can directly inform all drivers. So, NEXCO Central developed the system which transmitted the voice warning and the voice information directly to all drivers at an open space. And NEXCO Central installed this system in some expressway sites. As a result, it was confirmed that this system was effective in traffic safety measures.

Keywords: Voice warning; Open space; Traffic safety measures; Expressway

[1] * Corresponding author. Tel.: +81-52-212-4783;
E-mail address: h.takahashi.a@c-nexco-hen.jp

1. Introduction

The warning and the information provision for a driver are carried out by a traffic sign, an information board, an arrow sign, a sign on a navigation display, a flashing light and so on. According to Japan National police Agency, the cause of accident on an expressway were not to pay attention to the front (42%), not to watch the movement of surrounding traffic (22%), not to check safety (15%) and so on (Fig.1)[1]. These results showed that the driver who caused a traffic accident, did not pay attention to the front, or did not try to look forward, or was low wakefulness. In this situation almost all safety measures appeal to the driver's eyesight, so the current traffic safety measures are not sufficiently effective.

Recently, the case was increasing that the vehicle run into the lane restricted area for an operation on expressways in spite of installing the enough regulation signs and the enough attention attracting devices [2]. Some of them had caused accidents that hit and killed regulation operators and workers [3]. Based on these situation, Central Nippon Expressway Co., Ltd. (NEXCO Central) had been investigating the warning system that worked directly with the driver as an effective traffic safety measures. Then, NEXCO Central decided to develop the direct warning and information provision system to a driver using acoustic sense at an open space.

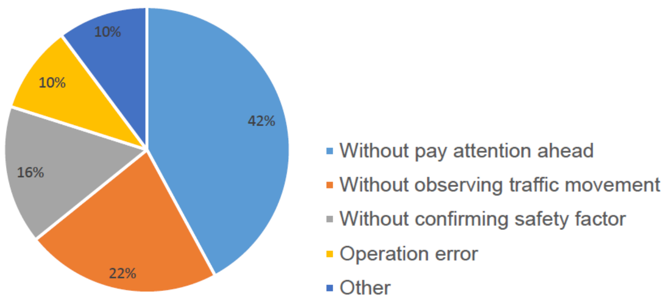

Figure 1: Violation trend of traffic accident on expressway

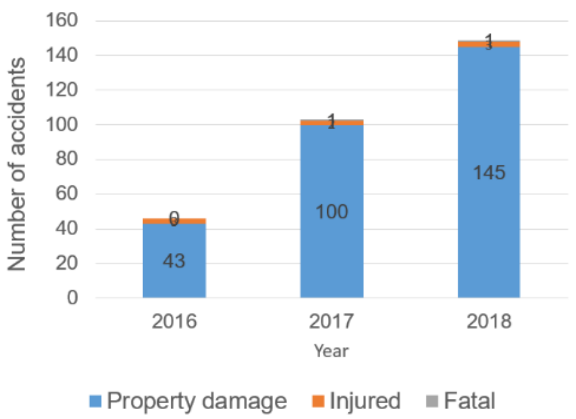

Figure 2: Number of accident entering the restriction area

2. Former Research

An arrow board, an information board and a flashing light are generally considered to be effective warning to drivers using visual sensation. But to appear the effect of a flashing light for safety measures, a driver needs to know the meaning of it beforehand. And also, a driver needs an enough distance from the information board in order to read the information, and moreover a driver needs to make a conscious effort to look at them. If not, they are not an effective warning for a driver [4]. Therefore, there is no effect in the case of driver's eyes without focusing forward, and this is the reason why many traffic accidents occur. On the other hand, a driver can hear a voice warning unconsciously, and a voice message itself can have a meaning of warning. And a driver can naturally recognize the content of voice message. Then generally, the warning using acoustic sense is more effective than the warning using visible sense. Moreover, according to the stimulus response, it is said that the response of acoustic stimulus is faster than that of visible stimulus [5].

The directly warning system to a driver by sound or voice already exists as a driving assist system, like a warning device and a road sign recognition system. However, these systems do not install all vehicle. For example, the road sign recognition system was installed in 30% of 2019 new car in Japan [6]. This ratio was estimated only 3% of all vehicle at the end of 2019 in Japan [6]. Recently, a system (road radio) has been developed that allows users to listen to present traffic information of a certain section by voice using a smartphone through the internet. However, this system also requires pre-configuration by a driver, and it can be expected that it will take some time before all drivers have smartphones and pre-configure their smartphones [7]. So, it will take a considerable amount of time for all vehicle drivers to be able to receive warnings. Therefore, the need for a system that can alert all drivers is considered to be extremely high for the time being. Moreover, the sound warning form outside has been used form a long time ago. However, these warning is only some kind of siren, or a voice warning system during a car stopping or running slowly, such as a guide speaker system in tunnel [8]. Recently, there are some trial to provide an information to a driver in a cabin by voice in a tunnel [9].

At open space, there were some proposals to radiate the warning beep to high speed running vehicles using highly directional speakers, such as a flat speaker [10][11]. But these systems radiated the warning beep to vehicles, and drivers needed to know the meaning of warning beep. It was meaningless when the driver did not understand what the warning beep was, and no direct effect could be expected to the driver. In some countries, voice alarm systems have been implemented and improved in tunnels because sound dose not spread easily in tunnels, dark noise is constant, and sound absorption is also constant [12].

On the other hand, until now, there was no system to transmit voice messages and warnings into a car cabin with windows closed at the open space, because of the difficulty to provide the audible voice message in a car cabin by sound diffusion, background noise in a car cabin (high-speed vehicle noise, such as wind noise, engine noise, road noise, etc.), sound absorption and high sound insulation during high speed running. This was the reason why to reproduce an audible voice in a car cabin with windows closed was exceedingly difficult with a high sound insulation to reduce a sound pressure during high speed running. But in a car cabin, a driver needed to hear the siren of an emergency vehicle, then some sound could transmit into a car cabin. So, if the sound were emitted to the cabin with a suitable position and direction, it was predicted that a driver who was in a cabin with windows closed could hear the voice coming from outside.

Considering the background noise in a cabin and the sound transmission property of car window glass, Kamekawa et al. confirmed that the suitable voice frequency to propagate into a cabin is from 500 Hz to 4 kHz, as a result of measuring the sound pressure in a cabin with window closed running 100 km/h on an expressway, making a sound from flat speakers on the road shoulder [13].

Yamamoto et al. conducted the experiment which they installed the 2 sets of 9 ultrasonic speakers in 5 m interval on the road shoulder and radiated the alarm and voice warning with inserting 16 mS delay into the sound from each speaker without time lag at a receiving point in a cabin. In this experiment, the drivers, 5 men and 4 women, in a passenger car, a SUV and a small truck, could hear the warning in 80 out of 81 cases [14].

And also, Yamamoto et al. measured the sound pressure to transmit the sound with changing sound radiation angle and distance in a passenger car cabin with windows closed, and after that with changing only sound radiation angle by the ultrasonic speakers [15]. As a result, they measured the highest sound pressure at 8 degrees in former case, and the highest sound pressure level at 0 and 22.5 degrees in latter case. In the case of the actual road, a speaker was installed in 5 m point from a vehicle running on a lane because of existing a guardrail, a road shoulder and a width of running lane. So, following 3 reasons, they considered that the best speaker angle was about 23 degree. The first is that on a real road, the distance between the speaker and the vehicle reduces the sound pressure level by 3 dB (A) in the driver's seat. Secondly, when the sound radiation angle is small, the distance between the sound source and the sound receiving point increases, and the upstream speaker is blocked by the downstream speaker sound. The third is that when the sound radiation angle is small, the sound source is blocked by other cars and many background sounds.

3. Investigation of More Audible Voice Message

Based on the above research, In order to find out how easy it is for drivers to hear the voice, we installed a tunnel phone speaker at the north entrance of the Akikawa tunnel, broadcasted voice information, and interviewed drivers who drove through this section to confirm the effectiveness of the system.

3.1. Outline

We installed 8 highly directional speakers in 350 m block (50 m interval, 4 m height) on a left shoulder, and they radiated the voice message to running vehicles. They radiated 2 type messages, such as 2 peaking speed and 2 different mute time between sentences. The message was “Please cooperate with a good parking manner at Atsugi rest area”. And we interviewed the driver at Atsugi rest area located after passing through Atsugi tunnel. The broadcasting sound pressure level in a cabin, 80 km/h running, in tunnel was 75-77 dB (A) with broadcasting, 68 dB (A) without broadcasting. The number of interviewee was 57, and the half of them got on passenger cars, about 80 % vehicle run on a running lane and the 40’s drivers was about 40 %.

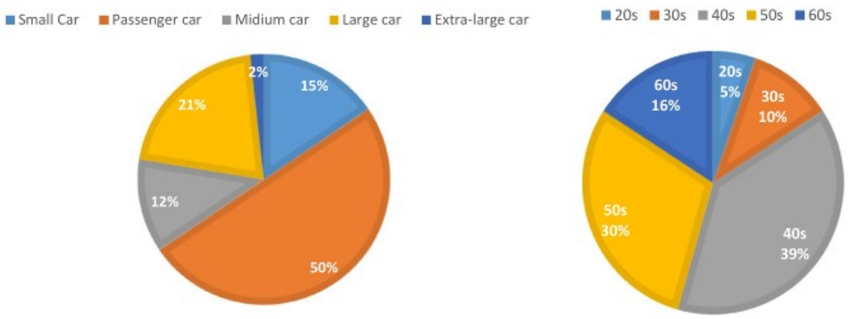

Figure 3: types of vehicles driven and age structure of drivers interviewed

3.2. Hearing Situation of Voice Message

96 % driver answered that they could hear the voice messages. The ratio of drivers who could hear them was almost the same on a running lane and on an overtaking lane. The driver who could hear the message, answered that they could recognize the content (90 %) and the main words (10 %). Based on analyzing the drivers’ action, despite of talking with passengers, listening to music, listening a radio and so on, there was no difference of drivers’ recognition. Then, we broadcasted 2 type messages, like a normal speaking speed (5.3S) and a slow speaking speed (6.8S) plus a long interval (0.5S) between “parking manner” and “Atsugi rest area”. Compared with them, the slow speaking message made higher recognition ratio than normal one despite drivers’ activities. 100 % drivers answered that they could hear the voice message a quite well and they could recognize the content well by the slow speed speaking message. So we found that the slow speaking made easy to hear for a driver.

3.3. Summary

From this result, we confirmed that the voice message was very effective for warning and providing information, because a driver could hear the voice message in any condition with windows closed, and we also confirmed that the effect could be improved with slower speaking speed. Based on above mentioned research, the users’ opinion to NEXCO Central Customer Center, the pre-interview of this experiment and the experiment result at Public Works Research Institute, we decided that it was necessary to consider the following points regarding the broadcast message.

1) The voice range was suitable from 500 Hz to 4 kHz, which was the lower noise level band in a cabin, and the around 2 kHz was the easy rang to hear.
2) The sound of line “U”, as “u”, “ku”, “su”, etc. in Japanese should be included in the message.
3) The sound of line “A”, as “a”, “ka”, “sa”, etc. in Japanese was appropriate to be lower sound pressure, because “a” in Japanese was heard like a siren.
4) The voice message should have an intonation and the silent gap should exist between words.
5) The message should consist of daily words.
6) A driver could easily recognize the message with repeating twice.
7) A female voice with high intelligibility was desirable.
8) Ultrasonic speakers have many problems that are difficult to solve in actual operation, such as poor durability, low attenuation, and difficulty in installation in places where there are houses.

4. Voice Warning System at Open Space

Based on these results, we conducted the voice message experiment at the southern entrance of Ogurayama tunnel on Kenou Expressway. This area was covered by a sound insulation wall, so we examined on the voice warning system with high directional and high flexibility flat speakers. And the effect was confirmed by interviewing the drivers of passing vehicles.

4.1. Speaker Arrangement

First, computer simulations were performed to determine the appropriate sound pressure distribution at the sound receiving position and the optimal speaker placement and angle. The sound pressure distribution was simulated with five speakers placed at intervals of 4 m and 8 m and at speaker placement angles of every 15 degrees up to 90 degrees (Fig. 4). The planar sound pressure distribution of this single flat speaker is shown in Figure 5, and at around 4000 Hz, where human sensitivity is highest, the difference between the front and back is about 30 dB(A), indicating that there is little sound diffusion except in the target direction.

Based on these results, it was decided to place speakers at intervals of 8 m for economic efficiency, because the range of high sound pressure is short at 4 m intervals, and even at 8 m intervals, if the angle is devised, the sound pressure distribution will not be extremely uneven, and the range of two lanes can be covered. The 20-degree angle was chosen because the speaker angles between 30 and 90 degrees tend to cause non-uniform sound pressure distribution radiated from adjacent speakers, the effect is small at 15 degrees, and the optimal radiation angle can cover more than two lanes, as discussed in Chapter 2, Section 3. The center position of the speakers was set at 1200 mm above the road surface to provide an optimal sound reception position for drivers of passenger cars, which are the majority of vehicles on the road. The number of speakers was set at 12 units, spaced at 8 m intervals, and placed over a length of 88 m. The sound pressure level at 1 m in front of the speaker was 105 dB (A) (800 Hz-8 kHz)

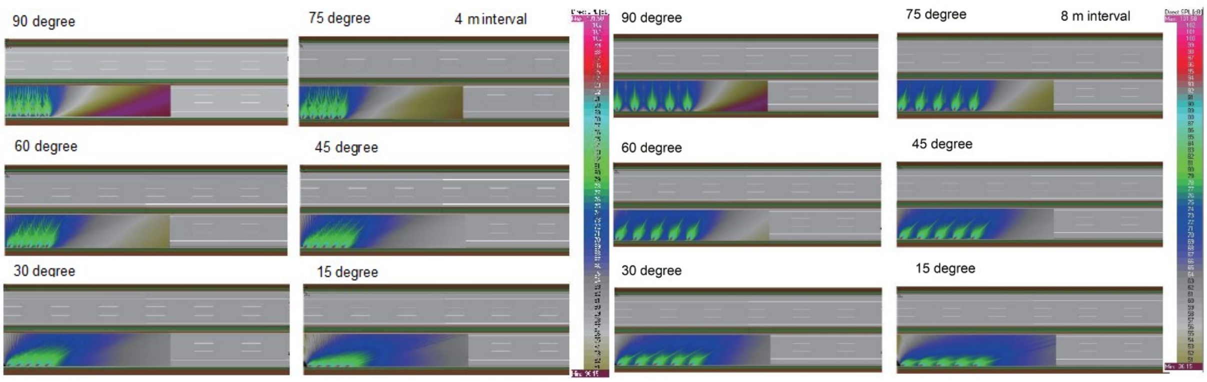

Figure 4: Sound pressure distribution by computer simulation (Left: 4 m interval, Right: 8m interval)

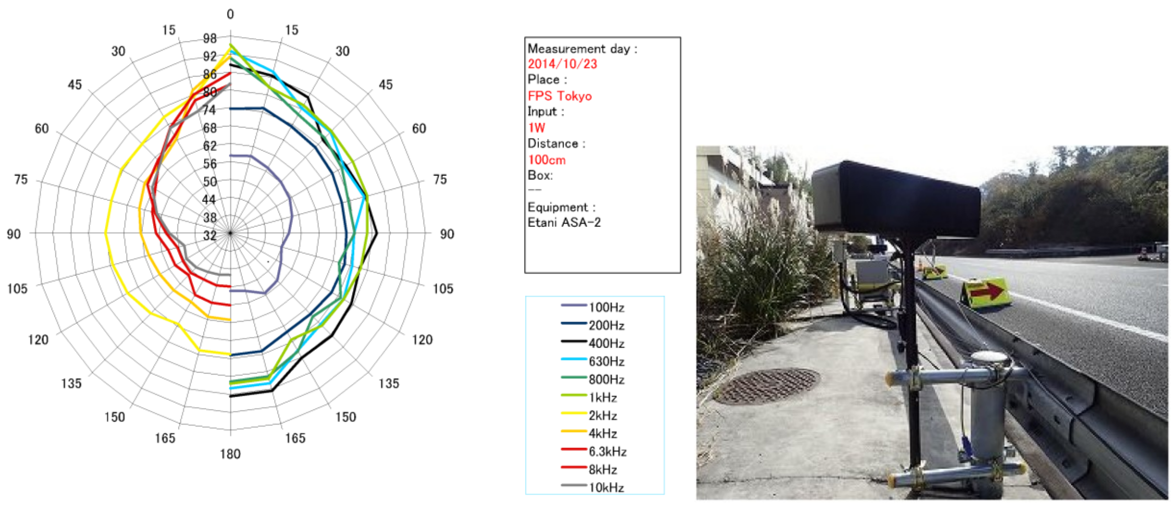

Figure 5: High directional and high flexibility flat speaker's sound pressure distribution chart and photo

4.2. Voice Listening Result while Driving

The driver in the vehicle traveling in the driving lane at a speed of 80 km / h is the subject of the audition. Since the extension was set at 88 m, it was decided to use the text "Please cooperate with good parking manners at Atsugi rest area" with a broadcast duration of approximately 3 seconds. When the vehicle was driven and auditioned under these conditions, the voice could be heard less than twice in the vehicle with the windows closed and the voice clearly audible. In addition, drivers who passed this section of the road indicated that they were able to hear the voice information.

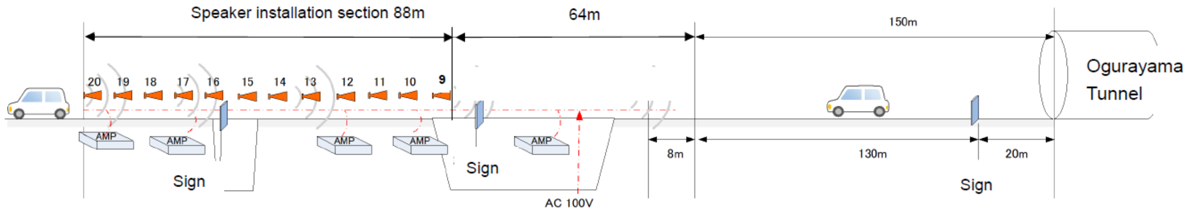

Figure 6: Test outline at Ogurayama tunnel

4.3. Summary

As a result of various experiments and simulations, we were able to develop a system for transmitting voice warnings to the inside of a moving vehicle in an open space. Since this system is designed for actual operation, it is capable of covering a certain section length with a small number of speakers to ensure that the voice is easily audible and can be installed at a reasonable cost. In addition, since many expressways have houses on the side, it was necessary to minimize sound leakage outside the road grounds. Then we were able to realize a system that can solve many of these issues.

5. Application as an Accident Countermeasure

Based on the above results, this system was installed into the curved section of approach ramp at Yokohama-Machida IC on Tomei Expressway as an accident mitigation measure through voice warnings to drivers. This section was an appropriate location for the introduction of voice warning to inform drivers of the road alignment in advance, as 18 lane departure accidents occurred during FY 2018, as well as accidents involving contact with protective barriers.

5.1. Accident Analysis and Target Area

The target location was the C approaching ramp of Yokohama-Machida IC in the downward direction on Tomei Expressway (Fig. 7). After passing the Yokohama Machida IC entrance toll booth, many accidents occur in the area just before the right curve underpasses the main line of the Tomei Expressway while descending at a maximum gradient of 5.8%, followed by a left curve (radius 42-44 m) with a maximum climbing gradient of 4.8%. Most of them are caused by excessive speed due to the downhill gradient and the subsequent left curve, and resulting in improper steering operation. For this reason, this system was installed before entering this curve, and provides drivers with information on the road alignment ahead and a voice warning of the “Sharp curve ahead”.

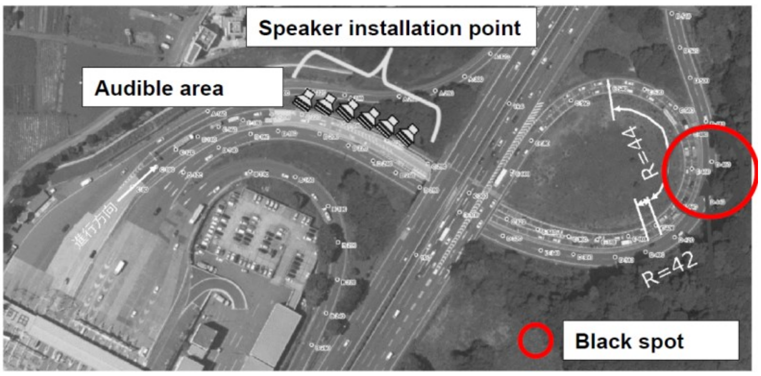

Figure 7: Outline of test area (C ramp at Yokohama-Machida IC)

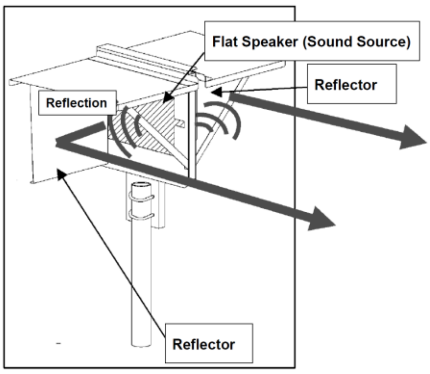

Figure 8: Speaker detail

5.2. Speaker Arrangement and Sound Pressure Level

The 6 speakers were placed 6 m apart, as shown in Fig. 7. Since the vehicle speed in this area was considered to be around 40 km/h, it was possible to secure more than 3 seconds of broadcast time, allowing the driver to hear the voice warning twice. Since the running speed is low and the sound pressure inside and outside the vehicle was also low, the radiated sound pressure was set to 95 dB (A), and the sound pressure inside the vehicle was set to 90 dB (A). The speaker angle relative to the vehicle was about 20 degrees because the ramp alignment was curved and vehicles entered from the broad Machida IC toll plaza, and a reflective plate was attached so that the sound would be directed directly to the vehicle. Prior to the event, the vehicle was driven and it was confirmed that the voice warning "Sharp curve ahead" could be heard inside the vehicle with the windows closed.

5.3. Investigation

To determine the effect of the system's installation, vehicle speeds were measured and compared before and after the system was installed. The average speed was calculated from the recorded data during the 35 m period before and after the point where the plane alignment was the tightest and where most accidents occurred. The measurements were taken for one hour (2414 samples) from 5-6pm on four days, July 28-30 and August 2, 2019, before the system was installed, and one hour (1763 samples) from 5-6pm on three days, August 30 and September 4-5, 2019, after the system was installed. These were the hours before sunset, when there was no rainfall. The vehicle whose speed was measured was the lead vehicle in a group of vehicles that was unlikely to be influenced by other companies. Based on the SURASAC report, such judgement was made for vehicles with an interval of 3 seconds or more from the vehicle in front [16].

5.4. Investigation Result

Figure 9-10 shows with and without system is displayed by velocity frequency of 2km / h for each large and small vehicle. For small cars, the frequency range is the same as 42-44 km / h, but it can be seen that the speed range above that is decreasing and the speed range below that is increasing. And in the case of having the system, the small vehicles average speed decreased 3.1 %. This trend was same as large vehicle with the mode of 36-38 km/h as the boundary. The average speed of large vehicle decreased 2.8 %. This was found to be a difference, at the 1% significance level. All vehicles average speed decreased from 42.2 to 40.5 km/h. This was statistically found to be different at the 1 % significant level. As shown in Figure 11-12, the decrease ratio in the left lane (close to the speaker) (4.3 %, from 41.2 to 39.5 km/h) was higher than that in the right lane (3.8 %, from 43.2 to 41.5 km/h). Normally, the left lane is considered a traveling lane, and is often traveled by large vehicles. The right lane is considered a passing lane and is often used by smaller vehicles. As you can see in Table 2, not only the average speed but also the maximum speed were reduced and the speed of $\mu + \sigma$ (85th percentile speed) were also reduced by -3.7% in the left lane and -2.5 % in the right lane. So, this indicated that most vehicles were slowing down. In addition, the rate of speed reduction is greater in the left lane and is considered to be more effective closer to the speakers. This may be because the right lane is further away from the speaker and the sound pressure is lower at the sound receiving point, and there may be a vehicle traveling in the left lane between the speaker and the vehicle receiving the sound, which may block the sound source. However, the impact was not so great, and it was confirmed that the running speeds in both lanes were decreasing.

5.5. Number of Traffic Accidents

The number of traffic accidents was compared to the one year period from September 2019 to August 2020 and the time period from September 2018 to August 2019 when the speaker was operating. As a result, as shown in Figure 12, the total number of accidents, 26 of which occurred before, was reduced to 4 after. Of these, 19 cases occurred before, but not after, when compered during the daytime non-jammed period when voice alert was provided. Of these 19 accidents, 17 occurred on wet surfaces and 2 on dry surfaces.

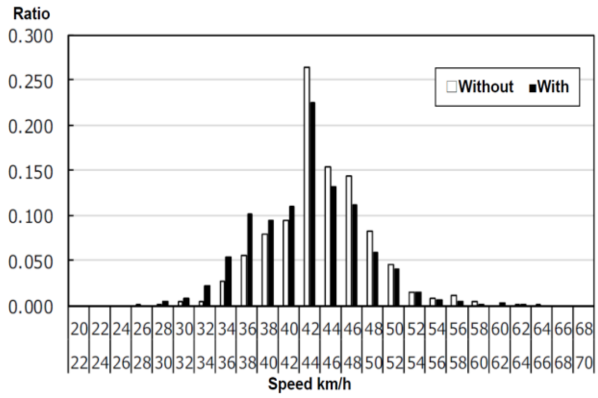

Figure 9: Speed distribution (Small car, All lanes)

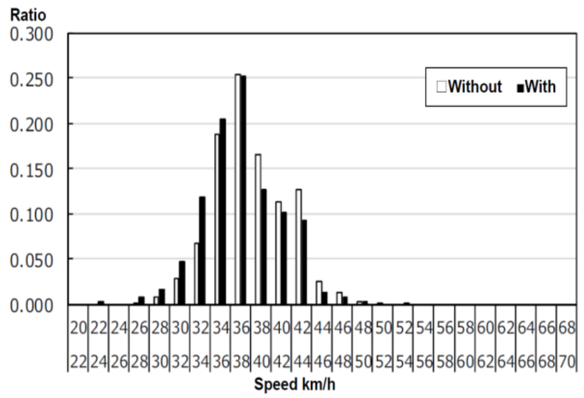

Figure 10: Speed distribution (Large car, All lanes)

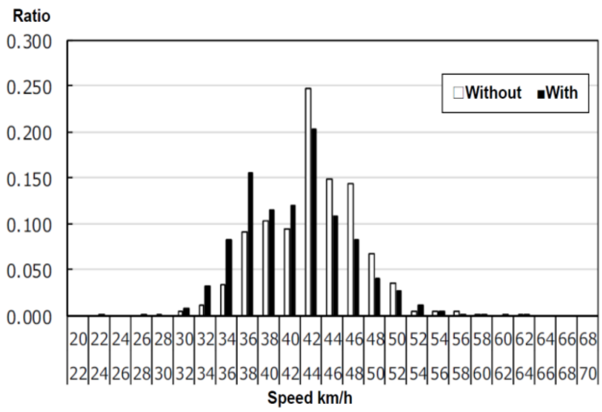

Figure 11: Speed distribution (All cars, Left lane)

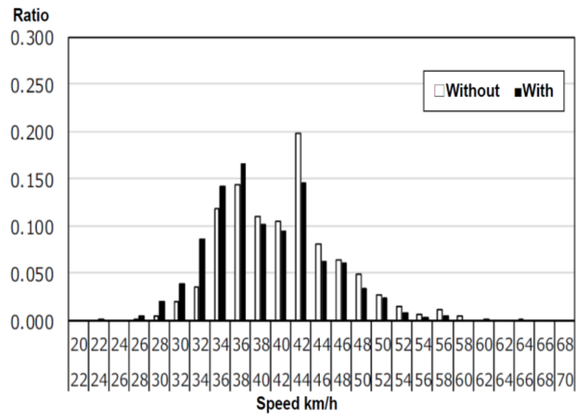

Figure 12: Speed distribution (All cars, Right lane)

Table 1: Speed change, with/without system (Vehicle type, All lane)

	Small Car			Large Car		
	Without	With	With/Without	Without	With	With/Without
Maximum value	65.1	62.9	-3.4%	50.4	52.4	4.0%
Average value μ	44.1	42.8	-3.1%	38	36.9	-2.8%
Standard deviation σ	4.7	5.1	8.8%	3.6	3.8	6.6%
$\mu + \sigma$	48.8	47.9	-1.9%	41.6	40.8	-1.9%
$\mu - \sigma$	39.4	37.6	-4.5%	34.4	33.1	-3.7%
Minimum value	27.8	28.2	1.4%	26.4	22.6	-14.4%
Sample	1,644	1,066		770	697	

Table 2: Speed change, with/without system (By lane: All vehicle)

	Left lane			Right lane		
	Without	With	With/Without	Without	With	With/Without
Maximum value	65.1	61.9	-4.9%	62.9	62.9	0.0%
Average value μ	41.2	39.5	-4.3%	43.2	41.5	-3.8%
Standard deviation σ	5.7	5.7	0.6%	4.5	5	10.4%
$\mu + \sigma$	46.9	45.1	-3.7%	47.7	46.5	-2.5%
$\mu - \sigma$	35.6	33.8	-5.1%	38.7	36.5	-5.5%
Minimum value	26.4	22.6	-14.4%	29.3	22.7	-22.5%
Sample	1,266	910		1,148	853	

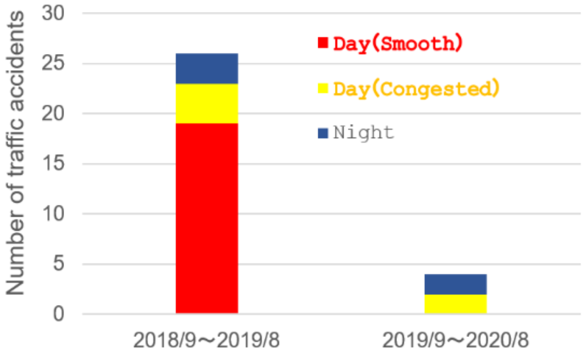

Figure 12 Number of traffic accidents with and without voice warning

6. Discussion

As confirmed in Chapter 3, It was proven that sound can be transmitted to the driver even in a car interior with the windows closed, if radiated at the appropriate sound angle, sound pressure level, and frequency. In addition, by using the appropriate reading speed, break time, sentence structure, and sound selection, it was possible to convey clear sentences to the driver inside the vehicle cabin. It was found that the best way to make voice warnings stand out in the interior noise of a traveling vehicle and minimize changes during voice propagation as it passed through the glass shield. Furthermore, almost all respondents indicated that they were able to hear and understand the voice guidance warnings while driving on the highway or doing whatever they were doing in the car. Thus, voice warning was confirmed to be a very effective means of communicating information and warnings to almost all drivers.

Also, as analyzed in Chapter 5, in this section, the number of accidents compared by whether or not the system provided voice warning decreased from 19 that had occurred in the prior period to 0. Since most of these accidents occurred on wet road surfaces, it is likely that the reduction in driving speed and the driver's alertness due to the voice warning had significant impact on reducing the number of accidents. And the 19 accidents that occurred during the year from September 2018, were mostly in the left lane, and this was likely due to the high rate of curvature, which made accidents more likely to occur. For this reason, this time, a voice warning was emitted from a speaker installed on the left side of the lane. As a result, the effect was stronger for vehicles traveling in the left lane, which are easier to listen to, and is thought to have contributed to the reduction in accidents.

Specifically, the maximum speed also decreased significantly in the left lane, down 4.9% for the left side, unchanged for the right side, down 3.4% for small cars, and down 4.0% for large cars, which is considered to have led to a reduction in accidents, in addition, a voice warning due to alert the driver.

Thus, by installing this system in this section where accidents occurred frequently, it was possible to confirm the effect on the driver by installing this system, such as reduction of travel speed and accidents.

However, until now, there has been no system to transmit clear voice warning into the traveling car cabin in an open space. In this study, we were able to develop a highly directional, water-resistant speaker and determine the appropriate radiation angle and placement of the sound, enabling us to develop a voice warning system for open spaces.

The newly developed system has made it possible to transmit voice warning to vehicles inside traveling in open spaces, which was difficult until now, until autonomous vehicles and vehicle equipped with next- generation driving support systems become widespread. Therefore, it is considered that the effectiveness of introducing it as an extremely effective safety measure in an open space was confirmed.

7. Conclusions

We have developed the system that broadcasts voice information in an open space to give effective information directly to drivers in a traveling car cabin with windows closed. This system is expected to provide information and reminders to all drivers, including those who are not aware of traffic safety. Such a system, which is given by voice, is expected to be more effective in reducing accidents and secondary accidents, since the information can be given to drivers individually and directly.

NEXCO Central has installed and is operating this system at several locations where information and warning are needed to reduce traffic accidents on expressways, reduce secondary disasters, and thus provide safe and secure expressways for all drivers.

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