Radio Wave Propagation Loss in the VHF to Microwave Region Due to Vehicles in Tunnels

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Abstract—**Electromagnetic field intensities in tunnels are measured in order to determine the effect that vehicles may have on radio wave propagation in the frequency range from VHF to microwaves. A**

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microwave simulation at 12 GHz was carried out in the vertical dominant mode in tunnels with arched and rectangular cross sections. It is shown that the propagation loss due to vehicles is determined mainly by their size and their number. The location of the vehicles in tunnels does not affect the propagation loss significantly.

I. INTRODUCTION

Many theoretical analyses and experiments have been conducted on radio wave propagation characteristics in hollow tunnels [1]–[7] from the viewpoint of wireless communication systems such as portable phones for emergencies and disasters. In general, tunnels may be regarded as oversized waveguides such that at microwave frequencies the attenuation is lower than in free space [4].

In the actual radio communications environment, however, propagation obstacles such as vehicles always exist. Hence, keeping in mind future developments in communications, it is worth investigating the propagation characteristics of radio waves in the VHF to microwave region in nonhollow tunnels (i.e., tunnels with obstacles).

To the authors' knowledge, only a few analytical investigations have been done on propagation characteristics within nonhollow tunnel structures [8]–[10]. Furthermore, how discrete obstacles affect the propagation characteristics and/or the propagation loss is still an open question. The difficulty stems from the inclusion of obstacles in an analysis: one deals with and needs to solve a complex three-dimensional problem in oversized lossy waveguides.

The purpose of this paper is to examine experimentally how obstacles in tunnels affect microwave propagation loss. The major emphasis of the study is on determining the propagation loss due to the following parameters: number, location, and size of vehicles, and cross-sectional shapes of tunnels. The laboratory experiment was performed using tunnel models with arched and rectangular cross sections. The dominant mode was transmitted into these tunnels from their entrances. We took different readings of field strength along the length of the tunnels to determine the effect that vehicles may have on the propagation characteristics. The scale ratio of tunnel dimension to the wavelength is about 2–3 in the experiment.

It is shown that the basic propagation loss due to vehicles in tunnels is determined mainly by the number and the size of the vehicles. Vehicle location and tunnel cross-sectional shape do not affect the propagation loss significantly.

II. MICROWAVE SIMULATION

We employed two double-lane tunnels made of styrofoam combined with carbon. The relative dielectric constant of the material is 1.3 and the conductivity is 0.17 S/m, which has been measured at 10 GHz by a standing wave method. The material is lossy enough so that no outgoing wave penetrates through the tunnel wall. In other words, the material acts like an actual concrete tunnel wall [4] at these frequencies. The block diagram for measuring the field strength in tunnels is shown in Fig. 1. One of the tunnels has an arched cross section 7.5 cm high and 10 cm wide. The other has a rectangular cross section 5 cm high and 8 cm wide. Both cross-sectional shapes are typical of actual tunnels.

The microwave transmitter (a rectangular horn antenna) is located at the entrance of the tunnel, from whence the vertically polarized dominant mode [2], [6] is transmitted. The relative field strength of this signal is then measured by a small dipole antenna at different points along the length of the tunnel. We used metallic miniature vehicles as obstacles (five cars, a van, a small bus, and a bus). They are shown in Table I.

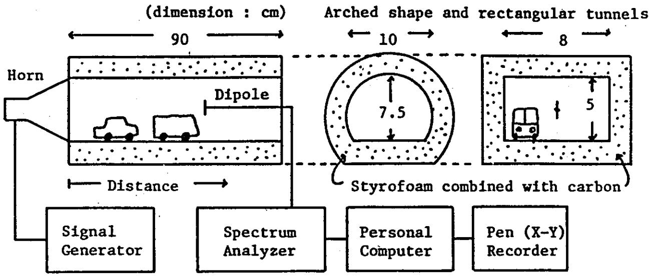
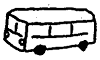
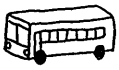


Fig. 1. Block diagram of arrangement to measure the field strength in tunnels.

TABLE I
VEHICLES USED IN THE EXPERIMENT

type	length (cm)	width (cm)	height (cm)	number	shape
sedan	7.0	2.5	2.0	5	
van	7.0	2.5	3.3	1	
small bus	10.5	2.5	3.0	1	
bus	13.0	3.3	3.8	1	

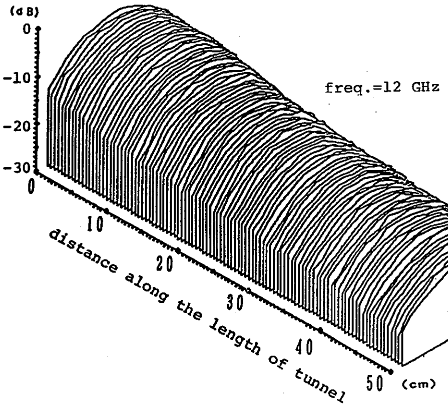


Fig. 2. Field pattern of the dominant mode in the arched tunnel without vehicles.

III. FIELD DISTRIBUTION

First, we measured the field pattern in the hollow arched tunnel to make sure that the dominant mode was excited. The pattern is shown in Fig. 2, based on measurements taken at 5-mm intervals on the plane parallel to the tunnel floor, at half the tunnel's maximum height. As can be seen, the pattern exhibits a clear distribution with one maximum of the dominant mode in the horizontal direction. The values of the field strength are relative, since this is sufficient to determine the propagation characteristics.

Next, we placed a bus in the left lane of the tunnel floor, 16 cm from the transmitter. We then repeated the procedure described above to take a new set of measurements of the field pattern. Fig. 3 shows the results as well as a shadow image of the tunnel floor that displays the position of the bus. It is seen that the pattern changes from that of the hollow tunnel. A standing wave phenomenon appears in front of the bus due to reflection and scattering. Instead of a one-maximum distribution in the horizontal direction, we now have a two-maxima distribution near the bus. The distribution in the region behind the bus starts off with a deep fading, which toward the end of

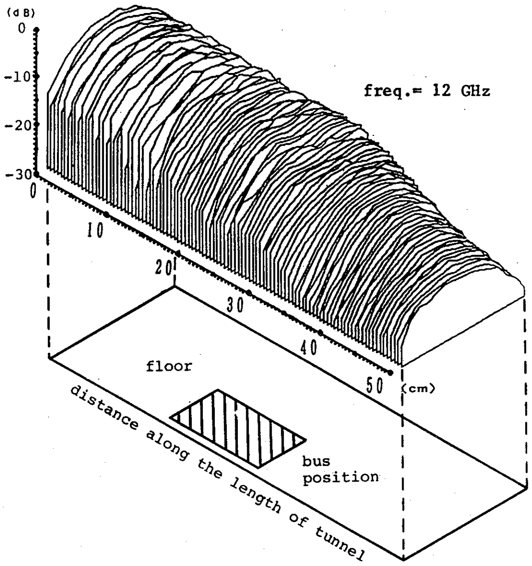


Fig. 3. Field pattern in the arched tunnel with a bus included.

the tunnel is transformed into a maximum distribution of the dominant mode.

Two further examples of the field pattern associated with vehicles are shown in Fig. 4(a) and (b). Both cases exhibit similar characteristics, except for the differences in field strength associated with vehicle size. Fig. 5 shows the pattern in the arched tunnel crowded with vehicles in the left lane. In this case, standing phenomena appear throughout the tunnel and the distribution is that of the dominant mode as a whole.

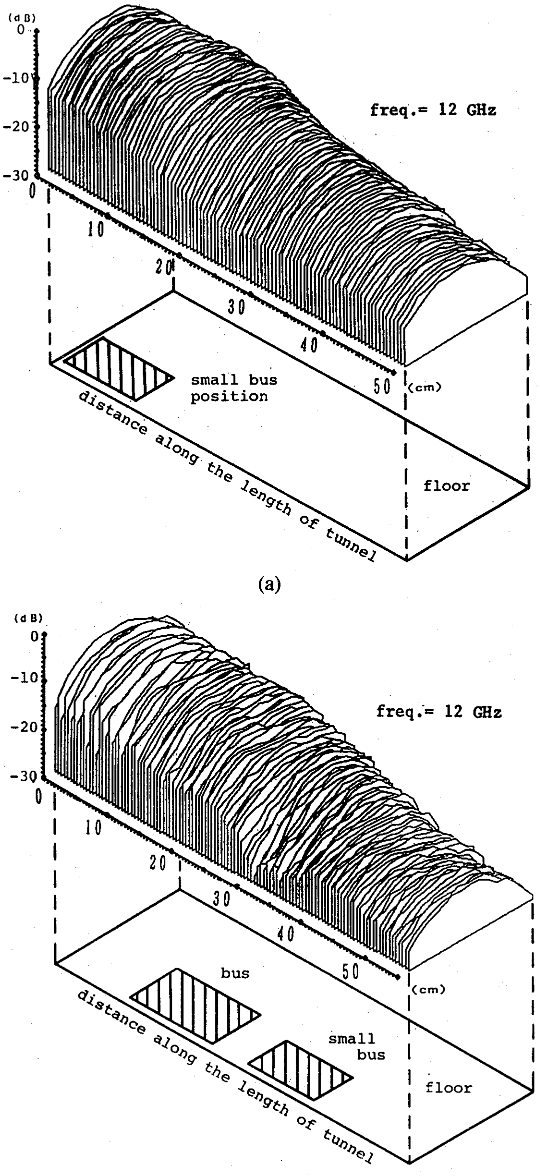
We refer to the region far from the vehicle as a stable region, where the field strength decreases monotonously with distance while holding the dominant mode pattern. We call the difference in field strength between the hollow tunnel case and the tunnel with vehicles case the propagation loss due to obstacles, as shown in Fig. 6. The total propagation loss is the sum of the loss due to the tunnel itself and the loss due to obstacles. The propagation loss caused by vehicles may be best defined by the differences in the field strengths in the region far from the obstacles, i.e., in the stable region. Thus, we employed the data in the hollow tunnel as standard data, with which we compared the other data.

IV. PROPAGATION LOSS

There are many parameters that affect the total propagation loss, for example, frequency, tunnel dimension, electrical properties of the tunnel wall, cross-sectional shape of the tunnel, vehicle size, shape, location, number, etc. Particularly, we examined the field strength variations dependent on the following parameters: vehicle size, location, and number, and cross-sectional shape of the tunnel.

A. Dependency on the Number of Vehicles

To examine how the propagation loss changes according to the number of cars in a tunnel, we measured the field strength using several sedan type cars. These cars were located in the left lane of the tunnels. Then the field strength was measured along the length of the tunnel at the center line of the cross section. Fig. 7(a) illustrates the experimental result. The readings of the field strength are repeated with 1, 2, 3, and finally 4 cars placed in the left lane of the tunnel. As shown by Fig. 7 the position of cars 1, 2, 3, and 4 is roughly 48, 36, 23, and 12 cm, respectively, from the entrance of the tunnel. The field strength changes rapidly near the cars. However, the differences in field strength due to the number of cars are clearly recognized only



(a)

(b)

Fig. 4. Field pattern in the arched tunnel with (a) a small bus and (b) a bus and a small bus included.

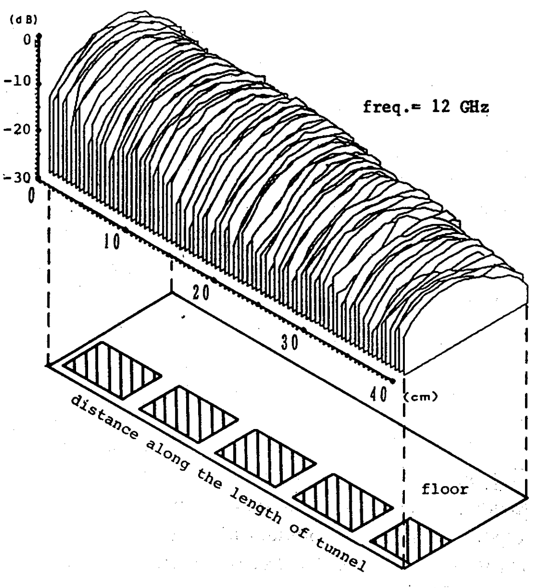


Fig. 5. Field pattern in the arched tunnel crowded with sedans.

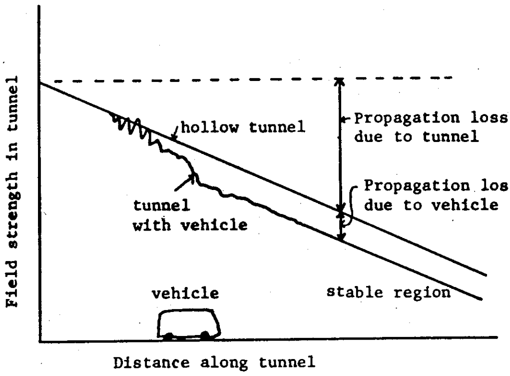
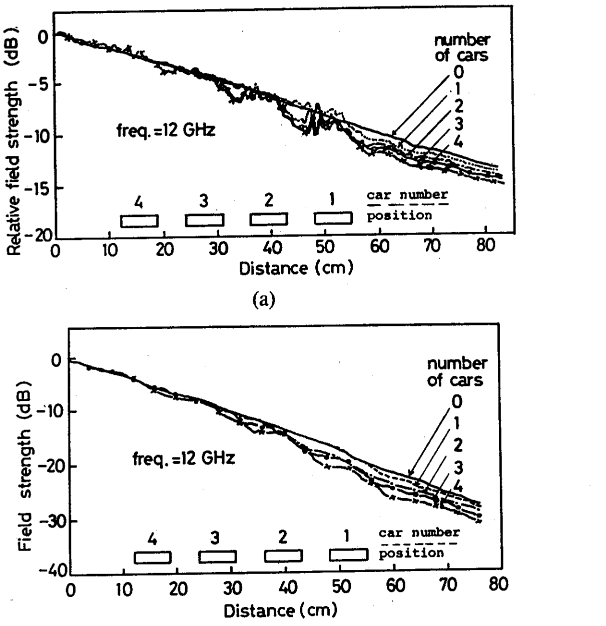


Fig. 6. Field strength and propagation loss in tunnels.



(a)

(b)

Fig. 7. Field strength measured along the center line of the cross section of (a) the arched tunnel and (b) the rectangular tunnel. (The numbered rectangular boxes show the car number and the position of cars.)

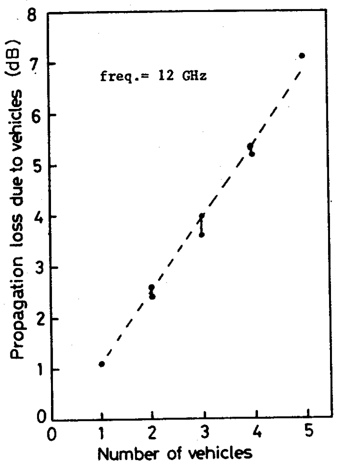
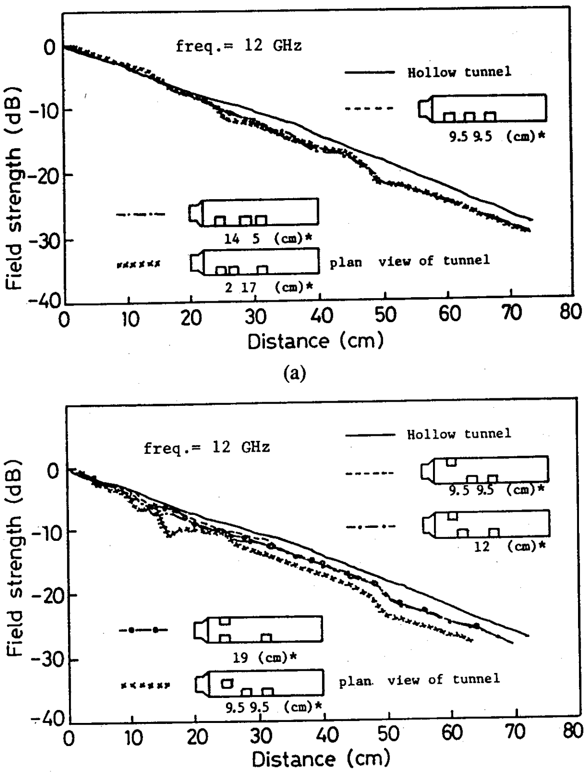


Fig. 8. Propagation loss in the rectangular tunnel versus number of cars.



(a)

(b)

Fig. 9. Field strength variation according to location of cars. (a) cars on one lane, (b) cars on both lanes.

in the stable region. The field strength is almost inversely proportional to the number of cars. This fact holds for the rectangular tunnel case as shown in Fig. 7(b). The fluctuations in the field strength in this case are less pronounced because the cross-sectional area is smaller than that of the arched tunnel.

The propagation loss due to the number of vehicles for the rectangular tunnel is shown in Fig. 8. The value of the propagation loss itself depends on various parameters. However, it increases almost in proportion to the number of vehicles, provided identical vehicles are used. The cross-sectional shape of tunnels does not affect the propagation characteristics (Fig. 7).

B. Dependency on the Location of Vehicles

Next, we examined the propagation loss due to the position of vehicles within the tunnel. The locations are indicated in Fig. 9 together with the field strength. The numerical values under the tunnel diagrams (plan view of tunnel) in Fig. 9 display the disposition of the vehicles. It is seen that the field strength does not change in the stable region as long as the number of vehicles remains the same. In other words, the propagation loss is determined by the number of vehicles regardless of their individual locations. One exception is the case in which a car is placed in the middle of the road (Fig. 9(b)). This is the position that most highly affects the distribution of the dominant mode. However, in ordinary circumstances, vehicles are in one of the lanes.

C. Dependency on the Size of Vehicles

It is well known that the scattering property of waves depends on the size of the scatterer. Different sized obstacles are expected to produce a different loss. Thus, we experimented with various sized vehicles located at the same point in the rectangular tunnel. The result is shown in Fig. 10, together with the location of the vehicles. As expected, vehicles whose size is large compared to the wavelength produce a larger propagation loss, and the scattering effects extend to the far region.

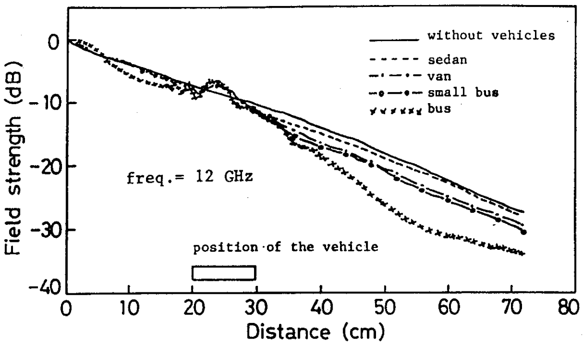


Fig. 10. The field strength due to vehicles of different sizes.

V. Discussion

The value of the total propagation loss in tunnels depends on many parameters, which can be classified roughly into two categories. The first group is related to the waveguide structures, for example: cross-sectional shape, size of tunnel, electrical properties of the surrounding medium, and signal frequency. The fundamental attenuation constant of the dominant mode in hollow tunnels varies inversely to the area of the tunnel's cross section [3], and to the frequency [4]. The other category groups those parameters that affect the scattering property of vehicles, i.e., the size to wavelength ratio, the shape, the location, and the number of vehicles. Thus, it is extremely difficult to analyze the propagation characteristics considering all parameters. In this microwave simulation, the fundamental properties of propagation loss due to vehicles were examined. However, the analytical study is left for a future investigation.

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References

[1] S. F. Mahmoud and J. R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels," *Radio Sci.*, vol. 9, no. 12, pp. 1147-1158, Dec. 1974.

[2] A. G. Emslie, R. L. Lagace, and P. F. Strong, "Theory of the propagation of UHF radio waves in coal mine tunnels," *IEEE Trans. Antennas Propagat.*, vol. AP-23, no. 2, pp. 192-205, Mar. 1975.

[3] J. Chiba, T. Inaba, Y. Kuwamoto, O. Banno, and R. Sato, "Radio communication in tunnels," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, no. 6, pp. 439-443, 1978.

[4] Y. Yamaguchi and T. Sekiguchi, "Attenuation constants of normal modes in hollow circular cylinder surrounded by dissipative medium," in *Proc. 1978 Int. Symp. Antennas Propagat., IECE Japan*, vol. c-3-3, pp. 385-388, 1978.

[5] B. Jacard and O. Maldonado, "Microwave modeling of rectangular tunnels," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, no. 6, pp. 576-581, June 1984.

[6] Y. Yamaguchi, T. Abe, T. Sekiguchi, and J. Chiba, "Attenuation constants of UHF radio waves in arched tunnels," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 8, pp. 714-718, Aug. 1985.

[7] Y. Yamaguchi, T. Abe, and T. Sekiguchi, "Experimental study of radio propagation characteristics in an underground street and corridors," *IEEE Trans. Electromagn. Compat.*, vol. EMC-28, no. 3, pp. 148-155, Aug. 1986.

[8] S. Kozono, T. Suzuki, and T. Hanazawa, "Experimental study of mobile radio propagation characteristics in rectangular tunnels," *Trans. IECE Japan*, vol. J62-B, no. 6, June 1979.

[9] J. Chiba and K. Sugiyama, "Effects of trains on cutoff frequency and field in rectangular tunnels as waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, no. 5, pp. 757-759, May 1982.

[10] Y. Yamaguchi, T. Abe, and T. Sekiguchi, "Radio propagation characteristics in underground streets crowded with pedestrians," *IEEE Trans. Electromagn. Compat.*, vol. 30, no. 2, pp. 130-136, May 1988.

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