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RESEARCH ON NEW ROAD TUNNEL LIGHTING AND SOOT EMISSION FOR VENTILATION DESIGN

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**RESEARCH ON NEW ROAD TUNNEL LIGHTING
AND SOOT EMISSION FOR VENTILATION DESIGN**

by

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Synopsis:

This paper is constructed by two studies concerned to of facilities attached to road tunnels . One is to system to be able to use counter - beam lighting (it is easy to find obstruct on road , and economical) in Japanese road traffical condition . Another is to unit of average vehicle emissions of soot which is one of injurious material and is considered in tunnel ventilation design .

Key Words: Tunnel, Design, Lighting, Ventilation

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1. Counterbeam Lighting Experiments in Full Scale Test Tunnel

1.1. Introduction

Ventilation and lighting systems are installed in road tunnels to ensure the safety and comfort of users. However, since tunnels are enclosed spaces, they are intimidating drivers, and are probably one cause of traffic congestion since drivers tend to slow down near tunnel entrances. Furthermore, as more roads have been built in recent years, the number of tunnels has increased remarkably, and costs associated with the construction and maintenance of ventilation and lighting systems have also risen. Hereafter, it is necessary to rationalize road tunnels to meet the needs for energy conservation, driving comfort, and high speed traffic.

As part of its overall rationalization of road tunnel design, the Public Works Research Institute (PWRI) is working to make tunnel lighting method more effective and efficient. From 1993 to 95, PWRI is conducting its Study on New Lighting Methods for Tunnel as a joint research project with Japan Highway Public Corporation; Metropolitan Expressway Public Corporation; Iwasaki Electric Co., Ltd.; Kenden Equipment Co., Ltd.; Koito Industries, Ltd.; Toshiba Lightech, Ltd.; and Matsushita Electric Industrial Co., Ltd. This three-year study is examining the adaptability of counterbeam lighting method used in Switzerland to traffic conditions in Japan. Compared to the symmetric lighting currently used in Japan, counterbeam lighting shows better contrast between obstructions and the road surface, making obstructions easier to see. Moreover, the method is more economical as it will be able to provide brighter luminance using the same amount of electricity.

According to Inokuma et al¹⁾, it is cleared that enhancing the contrast between the road surface and obstructions, counterbeam lighting makes visibility much better than in the symmetric lighting method. However, since in this research conventional lighting equipments with minor modification as to the distribution of light were used, the characteristics of counterbeam lighting was not well understood.

This paper will report on some of the results of this joint research using newly made counterbeam lighting equipment. In addition, since counterbeam lighting has been supposed to greatly improve lighting environment at tunnel entrances²⁾, research area is limited to entrance lighting in this investigation.

1.2. Description of the Counterbeam Lighting Method

The lighting method currently used in Japan beams light symmetrically in a vertical direction (Fig. 1.1a), thus it is called the symmetric lighting method. To the contrary, counterbeam lighting, as shown in Fig. 1.1b, beams light in the opposite direction to the traffic. This provides drivers with greater luminance of the road surface, resulting in greater contrast between the road surface and obstructions. Therefore, obstructions are seen as silhouettes, and perception and awareness of obstructions are so enhanced that lighting energy efficiency is greatly improved. Consequently,

costs for lighting equipment and maintenance may be reduced.

It should be noted that the CIE (International Lighting Committee) ³⁾ defines counterbeam lighting as lighting which has a contrast coefficient of 0.6 or more (contrast coefficient: the ratio between road surface luminance L_r and vertical illumination E_v); a contrast coefficient of 0.2 or less defines symmetric lighting.

1.3. Development of lighting equipment

Unlike symmetric equipment, the equipment used in counterbeam lighting beams light in the opposite direction that vehicles are traveling, thus making it necessary to consider ways of reducing glare to the driver. In developing our counterbeam equipment, we considered the light distribution like that used in Switzerland. As shown in Figure 1.2, equipment was so developed as would beam light to provide the greatest luminous intensity at a 60 degree angle from the vertical plane.

1.4. Counterbeam lighting experiment

1.4.1 Types and conditions of experiments

Experiments were conducted using both symmetric and counterbeam equipment at PWRI's experimental tunnel, which is at the same scale as an actual road tunnel. Experiments and measurements consisted of the following:

- a) Using optical measurements to understand basic lighting characteristics
- b) Experiments on the visibility of obstructions in a tunnel
- c) Experiments on the visibility of the vehicles (running ahead of the test vehicle) upon entering a tunnel

In addition, to compare the visibility and lighting characteristics of symmetric and counterbeam lighting, both methods were tested. At that time, lighting levels were set at a design speed of 60km/h, satisfying the current Standards for Lighting Facilities and Equipment of Road ⁴⁾. Moreover, since it was assumed that the illumination characteristics of counterbeam lighting would depend on the positioning of the lighting equipment, experiments were conducted under two conditions of positioning: equipment installed over lane center (hereafter called "center counterbeam lighting") and over road shoulders (hereafter called "shoulder counterbeam lighting"). Table 1.1 shows the main specifications and experimental conditions of the test tunnel. Obstructions used in the visibility and optical experiments were cubes (perimeter 20cm) and disks (23cm in diameter) with thick, unglossed paper for reflection ratios of 12%, 20% and 30% on the surface. Finally, for outside luminance to significantly affect the results in the visibility experiment, experiments were conducted only when outside luminance was at 3000 cd/m² or more

(sunny day).

1.4.2 Basic lighting characteristics through optical measurements

The measured items are the contrast coefficient by which the lighting method is distinguished and the average illumination conversion coefficients used when converting the horizontal road illumination of the road surface to road surface luminance. Since the values obtained depended on the type of road surface, small scale experiments were done using two 1800mm x 900mm pavement plates made of asphalt pavement and semi-flexible pavement respectively. The road surfaces of the plates were artificially abraded to make them resemble actual road surfaces, but since they did not necessarily simulate public road surfaces, those small scale experiments were used for reference only.

(1) Contrast coefficients

Measurements of vertical illumination E_v and road surface luminance L_r were taken on one lane at 15 points spaced at 10-meter intervals starting about 25-35 meters from the tunnel entrance. Vertical illumination was measured at 10cm above the road surface, while road surface luminance was measured at a height of 17cm about 13m away from each measuring point with an angle of declination of 1 deg and ocular/optic angle of 1/3 deg. The measured value(s) of the 15 points were averaged to obtain the contrast coefficient (L_r/E_v).

The results of the measurements are shown in Table 1.2. Here we can see that values differed widely depending on lighting method and type of road surface. Semi-flexible pavement showed the greatest surface luminance. In addition, with the exception of concrete pavement, counterbeam lighting was about 10% brighter than symmetric lighting.

The contrast coefficient for counterbeam lighting was smaller than the value set by the CIE. The reason for this was that to maintain continuity between tunnel entrance lighting and interior lighting, symmetric lighting was working at the same level of interior lighting through the entrance zone. When the fundamental lighting was turned off, the contrast coefficient for concrete pavement rose to about 0.52. The lighting method showing the highest contrast coefficient was center counterbeam lighting, and we could see that the ratio between surface luminance and vertical illumination was large, with obstructions showing higher visual contrast.

(2) Average illumination conversion coefficient

The average illumination conversion coefficient is the coefficient showing how-much horizontal illumination is required to obtain the unit luminance (1cd/m^2) on road surface. This coefficient is one of the indexes for showing the efficiency of lighting methods, which lower values signify greater economy.

Measurements of horizontal illumination and road surface luminance were taken on one lane at

15 points spaced 10m apart starting about 25-35m from the tunnel entrance. The measurement method for surface luminance was the same as that for the contrast coefficient, while horizontal illumination was measured above the road surface. The average illumination conversion coefficient K was derived from equation (1)

$$K = E/L_r \text{ [lx} \cdot \text{m}^2/\text{cd}] \quad (1)$$

where E is the average horizontal illumination (lx) and L_r is the average road surface luminance (cd/m²). The results of the measurements are shown in Figure 1.3. The average illumination conversion coefficient under symmetric lighting had been expected to be about 13 lx·m²/cd for concrete pavement and 18 lx·m²/cd for asphalt pavement. The values measured in the experiment showed a slightly higher value of 16 lx·m²/cd for concrete pavement. Reasons for this is considered that the surface of the concrete pavement remains rough in a transverse direction and there is almost no abrasion of the pavement caused by traffic flow. Therefore, compared to other, smoother sample road surfaces, the efficiency was slightly lower. However, semi-flexible pavement, which has come into greater use as tunnel pavement recent years, showed a low value of 10 lx·m²/cd, the most efficient of the three pavement types. Counterbeam lighting always showed lower values than symmetric regardless of road pavement such as by 70-80% for concrete pavement, by about 60% for both asphalt and semi-flexible pavement. From these results, we can see that the average illumination conversion coefficient depended not only on the lighting method, but also on the smoothness of the road surface. Therefore, to promote greater lighting efficiency, we should also consider the characteristics of the road surface the use of light-reflecting pavement materials.

1.4.3 Visibility experiments for obstructions in tunnels

Visibility experiments for obstructions in tunnels were conducted using 12 test subjects with normal vision and consisted of two types: stationary experiments (subjects were not moving) and moving experiments. The stationary experiments were designed to clarify how differences in reflectivity (caused by different lighting methods) affect visibility. The objectives of the moving experiments were to learn at what distance obstructions become visible from a moving vehicle, and how much glare there is from counterbeam lighting equipment when vehicles are in motion.

(1) Obstruction visibility (stationary experiments)

Stationary experiments involved the visibility of obstructions inside tunnels and at their entrances. Test subjects observed (from inside the stationary vehicle) the obstructions (20cm perimeter cube) which have the reflectivity ratios of 12%, 20%, and 30% for each at the distance of 75m from the obstruction. The visibility of these obstructions was subjectively evaluated. Furthermore, to evaluate the contrast of these obstructions, the vertical illumination (E_v) and

luminance (L_o) of the obstruction of 20% reflectivity, the road surface luminance (i.e., background) of four points around the obstruction were measured. The luminance of obstructions of 12% and 30% reflectivity was derived from the formula among luminance, vertical illumination and reflectivity ρ , as shown in equation (2):

$$L_o = (\rho \times E_v) / (100 \times \pi) \text{ [cd/m}^2\text{]} \quad (2)$$

(a) Contrast between obstruction and road surface

Ordinarily, contrast C is defined as an absolute value, but since it is easier to show how obstructions appear by using plus and minus symbols in this case, contrast was derived from equation (3)

$$C = (L_r - L_o) / L_r \quad (3)$$

The plus symbol means that the obstruction was seen in a silhouette, while minus means the inverse silhouette.

Figure 1.4 shows the changes in contrast of an obstruction of 30% reflectivity. Here we can see that for both types of lighting, there was negative contrast around the tunnel entrance, which became positive contrast upon proceeding in the tunnel. Because of this, when contrast was around 0, the obstruction became "extremely difficult to see." As the figure shows, counterbeam lighting tended to produce a rapid change from negative to positive contrast, reducing the range in which the obstruction was difficult to see. Hence, we can see that counterbeam lighting was much more effective than symmetric lighting in making obstructions visible around tunnel entrances.

Concerning the relationship between reflectivity and visibility, the more reflectivity increased contrast of the obstruction tended to change from negative to positive contrast the more gradually. In other words, contrast remained near 0 for long time, and the so-called "difficult to see obstruction" condition lasted a long time. This phenomenon was quite conspicuous with symmetric lighting, but no such noteworthy differences in obstruction visibility were seen in counterbeam lighting, regardless of reflectivity.

(b) Evaluation of obstruction visibility

Photos 1 and 2 show how an obstruction appears under different lighting conditions. Study subjects were asked to make a subjective numerical evaluation for the visibility of each obstruction. With the number of 5 representing the best visibility and 1 the worst, each type of lighting method was evaluated.

Figure 1.5 shows changes in average values based on the above evaluations for 30% reflectivity obstruction. The evaluation values are got from the average of the evaluations of all test subjects.

Here there were no noticeable differences in lighting methods at points of 0m, 20m, and 40m, where sunlight could still enter the tunnel. However, at 60m, symmetric lighting was rated lower than counterbeam lighting. This trend showed relatively good correspondence with contrast results, that is, the higher the contrast, the higher the evaluations of the test subjects.

Figure 1.6 shows the relation between contrast and average values from the questionnaires. To obtain the evaluation numbers of 2 (little visibility) and of 3 (average visibility) from the regression line in the figure, contrast must be at least 0.18 and 0.65, respectively. The correlation coefficient at this time was 0.67.

(2) Obstruction visibility (moving experiment)

For the moving experiment, subjects were asked to drive 60km/h into a tunnel and view two types of obstructions (cubes and disks) with 30% reflectivity at designated points in the tunnel. At this time, the visibility distance was measured. Immediately after the experiment, subjects were given a questionnaire to evaluate the following items on a one-to-five scale: 1) visibility of tunnel entrance, 2) ease of tunnel entry, 3) glare from lighting equipment, and 4) the visual environment of the tunnel immediately after entry. It should be noted that "visibility distance" is "the distance at which an obstruction can be seen but not be identified." Each experiment was conducted twice under the same conditions.

(a) Comparison of visibility distances

Figure 1.7 shows a comparison of visibility distances (average values for all test subjects) for counterbeam lighting with visibility distances for symmetric lighting. Here we can see that the visibility distance for center counterbeam lighting at the obstruction position of 40m from the entrance was less than that of symmetric lighting, but counterbeam lighting showed higher values at all other positions. At positions beyond the 80m from the tunnel entrance, which are almost unaffected by sunlight, counterbeam lighting showed visibility 1.5-2.5 times higher than symmetric lighting, leading to the conclusion that the lighting method affects visibility.

(b) Questionnaire results

Figure 1.8 shows the results of questionnaires on concerning glare from lighting equipment. According to the figure, glare, which had been supposed to be with counterbeam lighting, was not a problem. Figure 1.9, where higher values signify higher evaluations, shows four types of questionnaire results. Here we can see that, except for glare from lighting equipment, counterbeam lighting was more highly rated than symmetric lighting.

(3) Visibility of other vehicles in front of driver (moving experiment)

Since counterbeam lighting does not beam light on to the rear end of other vehicles running in

front of the driver, it was predicted that this method would provide less visibility than symmetric lighting near the tunnel entrance, where brightness suddenly changes. Test subjects, who drove into the tunnel at 60km/h, were asked to subjectively evaluate, on a scale of 1 to 5, visibility at the time of entering tunnel. The objects of this visibility questionnaire were large and small vehicles, and small vehicles traveling behind large vehicles. Subjects were asked to make observations at vehicle intervals of 20m, 40m, and 80m one time respectively (total three times).

The visibility immediately after tunnel entry of large vehicles in front is shown in Figure 1.10. The values were calculated from the arithmetic average of evaluations of all subjects. Here we can see that, as vehicle intervals increased, evaluations values fell, and there was no noticeable difference between lighting systems. Therefore, we could see that artificial lighting had little effect on the visibility of other vehicles running in front of drivers. The same kinds of results were obtained under the different type of vehicle.

1.5. Conclusion

In applying counterbeam lighting in Japan, special lighting equipment was developed, basic lighting characteristics, the visibility of leading vehicles and glare from lighting equipment, etc., were investigated and it provides the following information:

- 1) The effectiveness of counterbeam lighting depends on the type of pavement and the smoothness or roughness of the road surface.
- 2) In daytime, obstructions disposed at the points of 20-60m from the tunnel entrance are difficult to see, regardless of lighting method. In addition, under symmetric lighting the visibility of objects is affected by their reflectivity, but there is very little effect from obstruction reflectivity under counterbeam lighting. Furthermore, the area where obstructions are difficult to see is smaller in counterbeam than in symmetric lighting.
- 3) The visibility distance from a moving vehicle of an obstruction under counterbeam lighting is usually greater than symmetric lighting, although there are a few exceptions.
- 4) There is no special glare caused by counterbeam lighting equipment; moreover, counterbeam lighting is much better than symmetric lighting for visibility at tunnel entrance, ease of tunnel entry, and visual environment immediately after tunnel entry.
- 5) The visibility of other vehicles running in front of drivers is not affected by lighting methods; the expected decrease in visibility under counterbeam lighting was not apparent.

1.6. Future research topics

To effectively and efficiently design counterbeam lighting, it is very important to clarify the relationship between lighting effectiveness and the types of road surfaces since lighting effectiveness is greatly affected by road surface conditions. We must also investigate the safety and practicability of this new method for high speed driving. Moreover, to further enhance safety, we

must confirm visibility and qualitatively evaluate the effects of shading caused by large vehicles and the effects of the vehicles traveling very close together.

Finally, it will be necessary in the future to install counterbeam lighting on an experimental basis in actual tunnels and investigate the results thereof.

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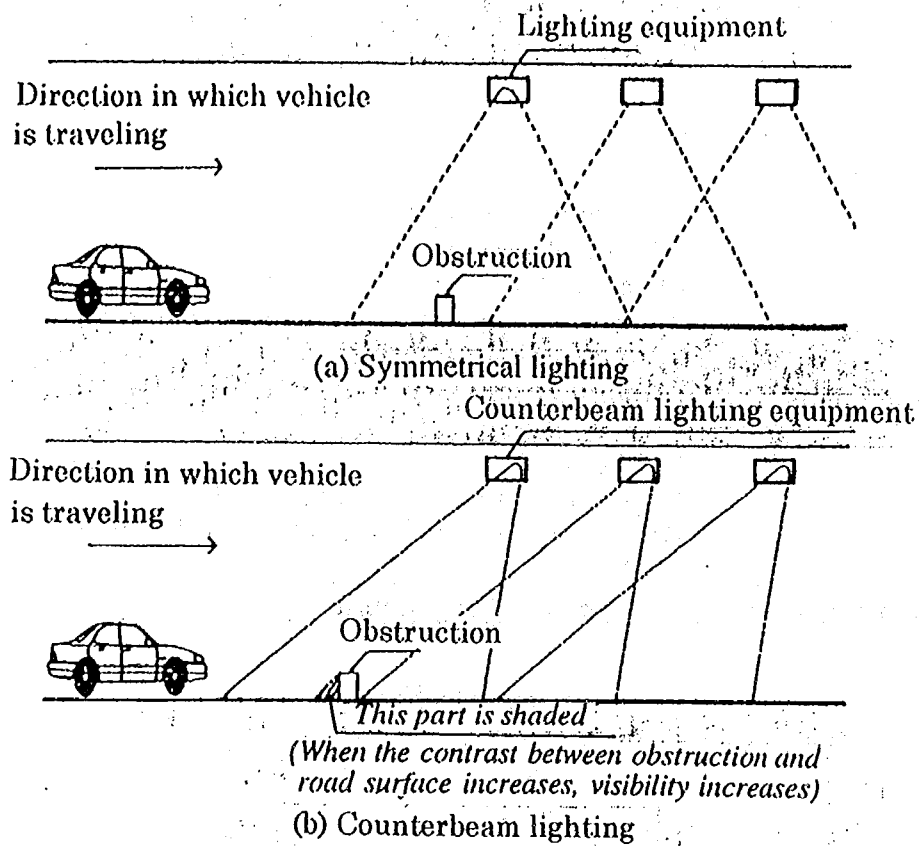


Figure 1.1 Diagram of tunnel lighting methods

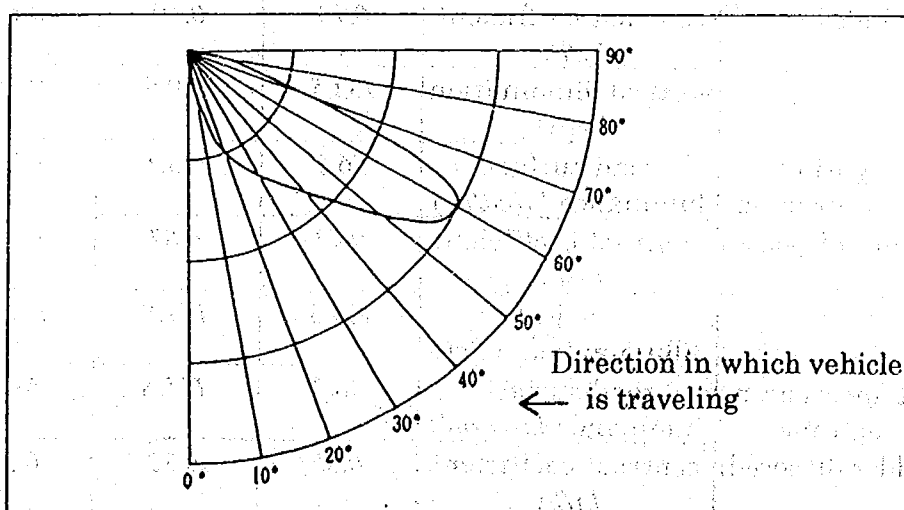


Figure 1.2 Light distribution of counterbeam lighting equipment

Table 1.1 Experimental conditions

Tunnel length	700m
Sectional area	53.7m ² (2 lanes)
Pavement	Concrete (rough finish)
Lighting methods types of lamps	• Symmetrical lighting High and low pressure sodium lamps (lighting equipment installed for general use) • Counterbeam lighting High pressure sodium lamp (Installed as newly developed lighting equipment) • Others Low pressure sodium lamp (lighting equipment installed for general use for inner lighting)
Lighting level	lighting level at 60km/h

Table 1.2 Characteristics of various types of road surfaces

Road surface		concrete pavement	semi- flexible pavement	asphalt pavement
Item				
Symmetric lighting	vertical illumination $E_v(lx)$	499.0	535.6	451.9
	road surface luminance $L_r(cd/m^2)$	65.4	102.0	59.7
	contrast coefficient L_r/E_v	0.13	0.19	0.13
lighting Counterbeam (center disposed)	vertical illumination $E_v(lx)$	133.5	129.6	91.8
	road surface luminance $L_r(cd/m^2)$	56.5	113.1	67.2
	contrast coefficient L_r/E_v	0.42	0.87	0.73
Counterbeam lighting (shoulder disposed)	vertical illumination $E_v(lx)$	159.3	161.8	117.0
	road surface luminance $L_r(cd/m^2)$	56.3	115.8	69.5
	contrast coefficient L_r/E_v	0.35	0.72	0.59

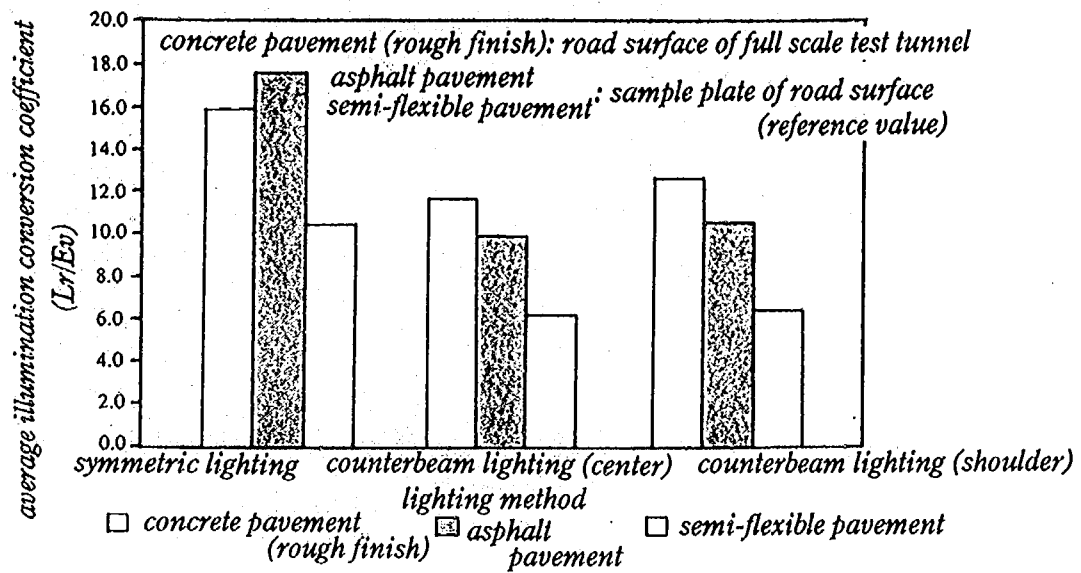


Figure 1.3 Comparison of average illumination conversion coefficient

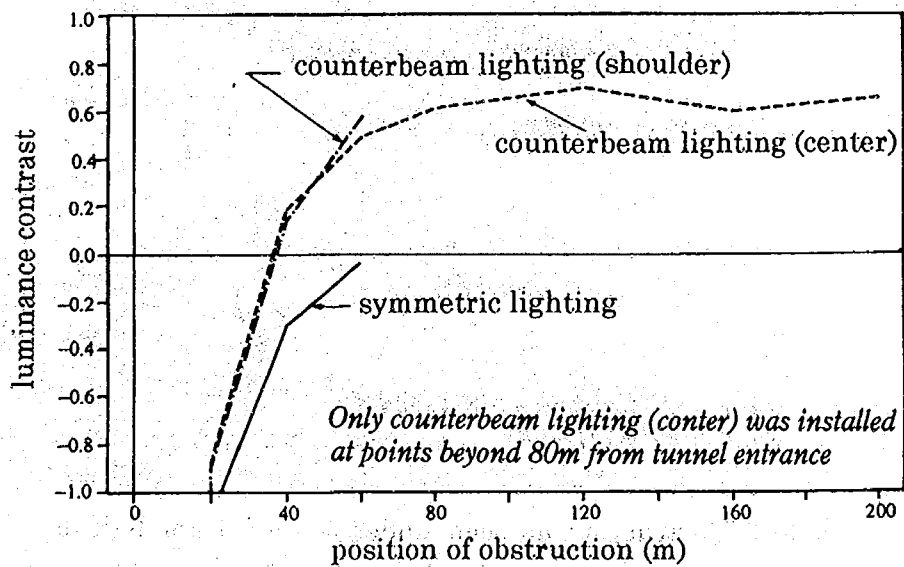


Figure 1.4 Relation between contrast and position of obstruction (30% reflectivity)

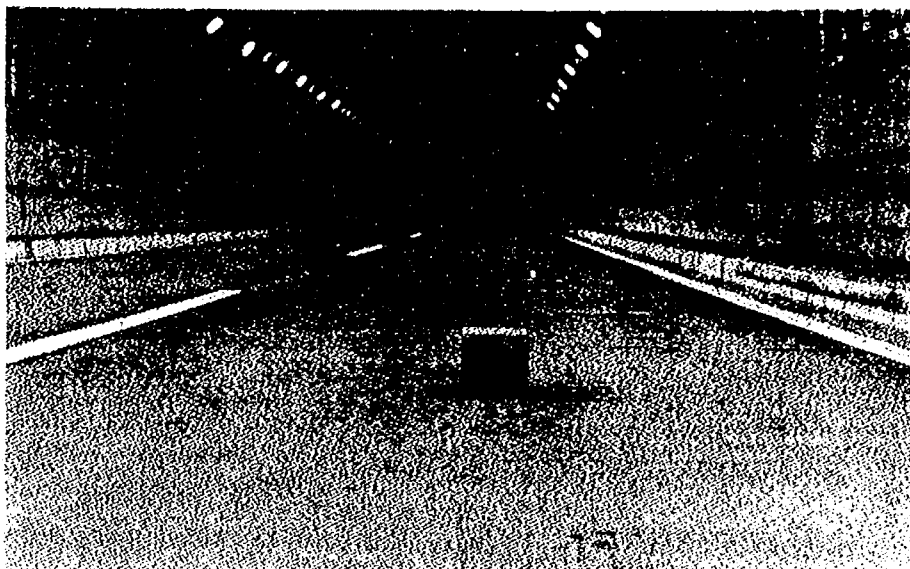


Photo 1 Obstruction as seen under symmetric lighting
(30% reflectivity, 60m from tunnel entrance)

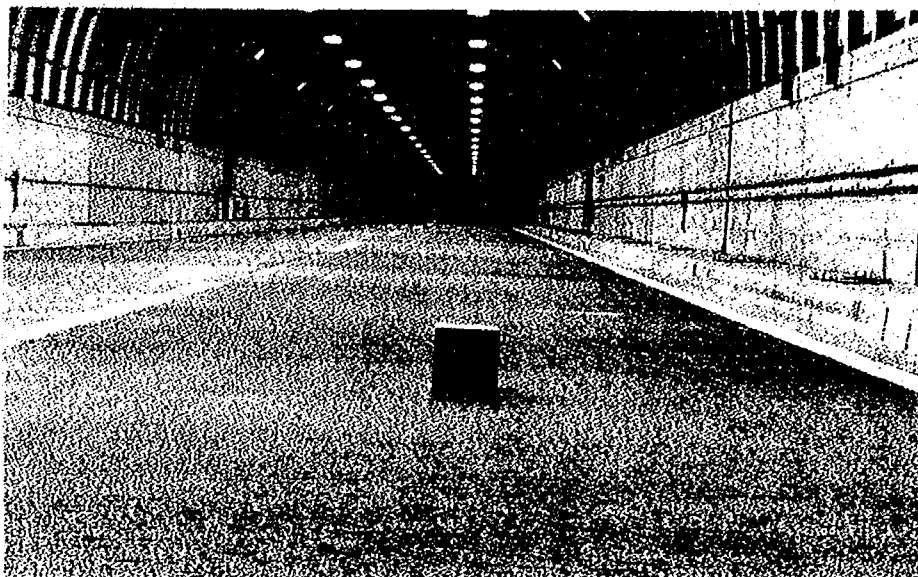


Photo 2 Obstruction as seen under counterbeam lighting
(center) (30% reflectivity, 60m from tunnel entrance)

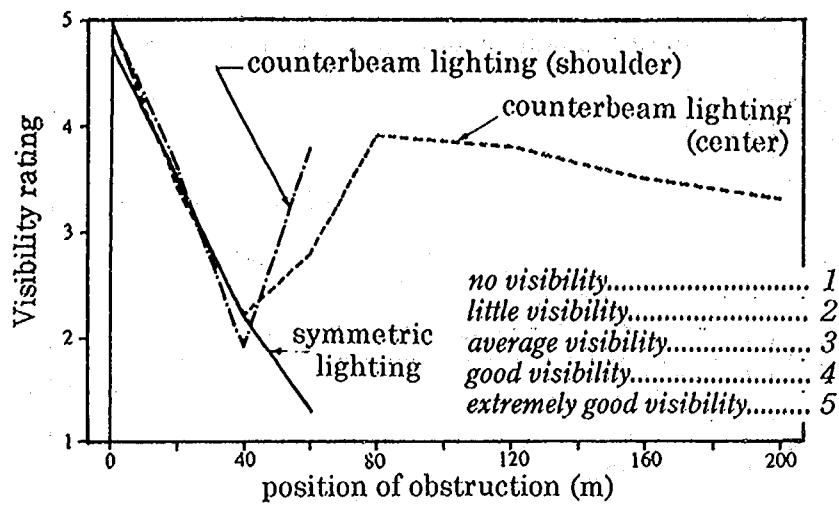


Figure 1.5 Visibility evaluation of obstruction for each position (30% reflectivity)

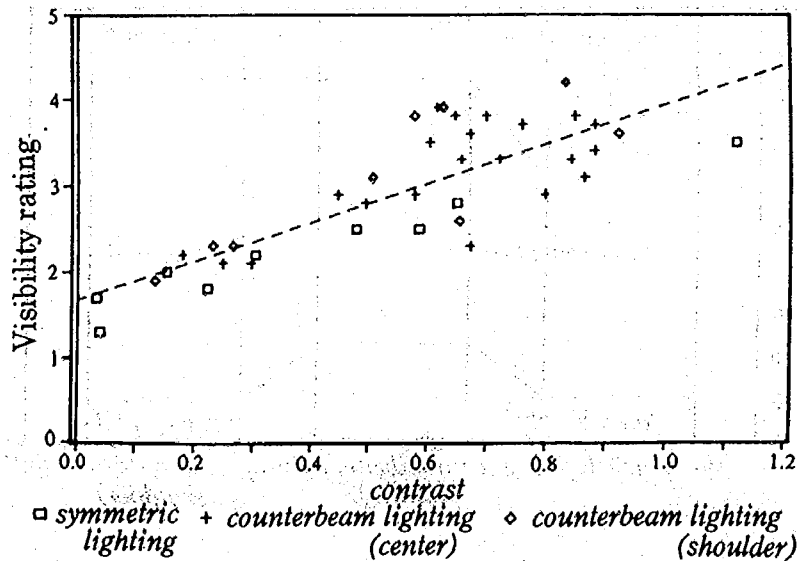


Figure 1.6 Relation between contrast and visibility rating

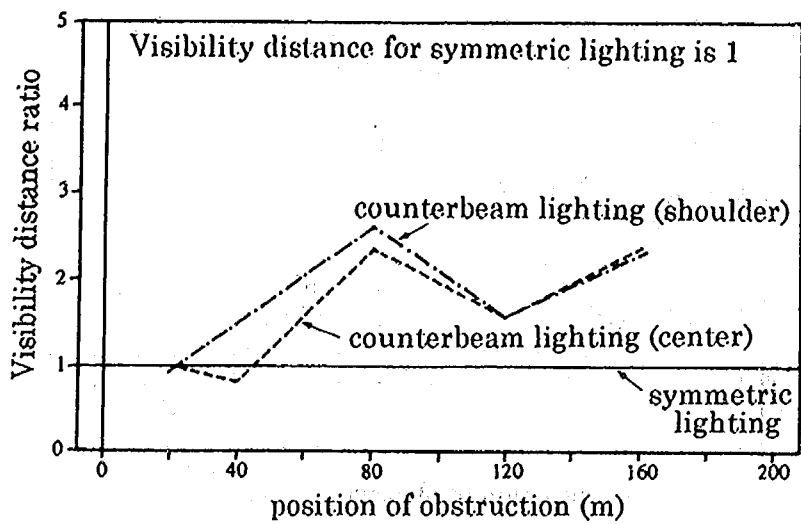


Figure 1.7 Ratio of visibility distances of counterbeam lighting

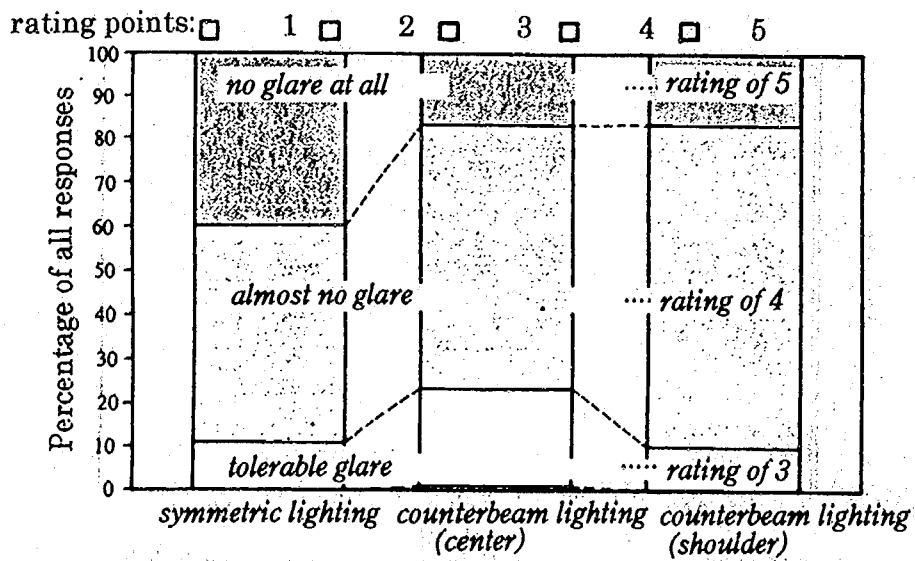


Figure 1.8 Glare from lighting equipment

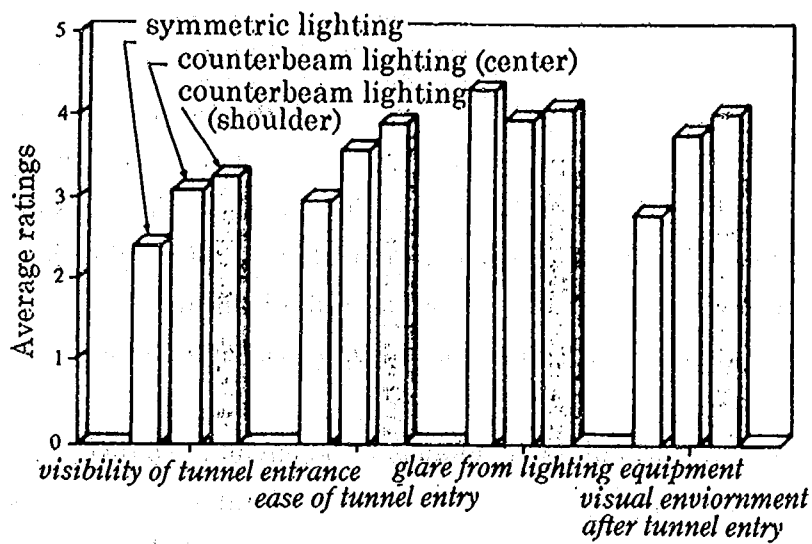


Figure 1.9 Results of questionnaire for moving experiment

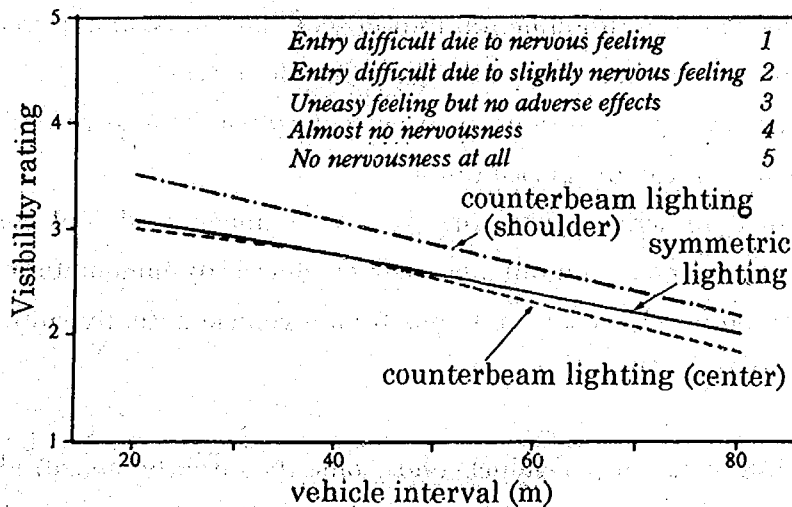


Figure 1.10 Results of visibility experiments
with other large vehicles running in front of driver
Figure 1.10 Results of visibility experiments
with large vehicles in front of driver

2. Vehicle Emissions for Road Tunnel Ventilation Design

2.1. Introduction

Ventilation, lighting, and emergency equipment are installed in road tunnels to make driving there safer and more comfortable. Ventilation equipment affects the structure design of tunnels and requires considerable expenditures for installation, maintenance, and management. Therefore, studies must be sufficiently undertaken before installation begins. The noxious substances which are the object of ventilation design have been determined by road tunnel technological standards to be soot and carbon monoxide (CO). The present standard for unit emissions of these noxious substances (see Tables 2.1 and 2.2) are based on the values derived from in situ survey data taken in the late 1960s.

However, subsequent improvements in automobile design and exhaust gas regulations probably have helped to reduce unit emissions, so it is very important that we reconsider these values. Therefore, by the PWRI, in situ surveys have been conducted during the past two years in conjunction with the Japan Highway Public Corporation and the Metropolitan Expressway Public Corporation to gain an understanding of new vehicle unit emissions. The results of this research will eventually be reflected in revised technological standards of ventilation. Since unit emissions of soot are believed to have an especially large influence on ventilation design, they will be the subject of this report. We are also continuing our investigations of the other toxin, CO.

2.2. Methodology

2.2.1 Selection of measurement method

The research methods for the fundamental unit of soot emissions, and correction coefficients of speed, gradient and altitude are basically of the following three types:

- 1) an indirect method in which conditions such as soot transmittance rates, wind speed, traffic volume, etc., are measured in the in-service tunnels,
- 2) a "laboratory" method in which an engine is placed under load and concentrations of its emissions are directly measured at the tail pipe, using a chassis dynamometer,
- 3) a "running test" method in which the emissions from a vehicle actually running on the road are directly measured.

Generally, as an absolute value of per-vehicle emissions, the directly measured values (laboratory and running tests) were lower than the values derived from the indirect method. Presumed reasons are that the soot transmittance rates obtained by the indirect method may have been affected by changes in carbon particulate and airborne dust, and sand brought in from outside the tunnel. Regardless of the reason, however, since the emission units derived from indirect measurements were back calculated from the visual environment of the tunnel interior, they are believed to

represent values closer to actual conditions. Therefore, the fundamental unit emissions should be obtained through indirect measurements.

The speed, gradient and altitude correction coefficients were also derived from indirect measurements, and are believed to be suitable for ventilation design calculations. However, a large number of indirect measurements would be needed, if whole coefficients of all different conditions are to be got by this method. Therefore, direct measurements obtained from laboratory experiments were used for the speed and gradient correction coefficient.

Finally, since it was extremely difficult to establish the proper laboratory conditions (e.g., atmospheric pressure, temperature), it was decided to derive the altitude correction coefficient using indirect measurements to confirm the suitability of current standards.

2.2.2 Site survey (Indirect method)

A site survey was conducted in the tunnel to get the total per-vehicle emissions from the concentration distribution formula of various ventilation methods and from the measurements of in-tunnel noxious concentrations (soot transmittance rate, CO concentrations, etc.), wind velocity, and traffic volume. In-tunnel of longitudinal ventilation methods, ventilation conditions are shown in Figure 2.2. The emission rate of noxious substances discharged by vehicles per meter of tunnel length (noxious concentration $\times$ volume of emissions) is shown by P (unit/s(m)). Assuming that P is uniformly emitted within the tunnel, the distribution of concentrations within a traffic lane $C(X)$ (unit/m³) can be expressed by the following formula:

$$C(X) = \frac{P \times X}{Q_0} + C_0 \quad (1)$$

Here, X is the distance (m) from the tunnel entrance, Q_0 is the fresh air intake (m³/s) from the tunnel entrance, and C_0 is outside concentrations near the tunnel entrance (unit/m³-- usually, $C_0 = 0$ is acceptable). Q_0 was expressed in the following equation using the traffic lane wind velocity V_r (m/s) of the tunnel interior and the sectional area of the tunnel (A_r (m²)).

$$Q_0 = A_r \times V_r$$

From equation (1), concentrations at observation points (shown as subscript 1 in the following equation) could be expressed by

$$C_1 = \frac{P \times l_1}{Q_0} + C_0 \quad (2)$$

where l_1 is the distance (m) from the tunnel entrance to the observation point. When we express average per-vehicle emissions of noxious substances as μ (unit/veh·m), μ can be derived from the following equation using P (unit/s·m) which is the emission rate of noxious gases discharged by vehicles per 1m of tunnel length and hourly traffic volume N (veh/h):

$$\mu = \frac{P \times 3,600}{N} \quad (3)$$

Substituting equation (2) with equation (3) gives us

$$\mu = \frac{3,600 \times Q_0}{N l_1} (C_1 - C_0) \quad (4)$$

Here, Q_0 can be obtained from traffic lane wind velocity in the tunnel, N from the hourly traffic volume, and C_0 and C_1 from observed concentrations. We are able to calculate the average emission volume μ of noxious gases per vehicle.

The site survey was conducted at 6 tunnels: Tunnel A (National highway Route 1), Tunnel B (Chuo Expressway), Tunnel C (Kyushu Expressway), Tunnel D (Sanyo Expressway), Tunnel E (Hokuriku Expressway), and Tunnel H (municipal road tunnel in Hyogo Prefecture). Measurements were taken for a continuous period of 48 hours. These particular tunnels were chosen because it was believed that the correction coefficients for gradient and altitude could be obtained from the survey results at these locations.

Table 2.3 outlines the tunnels which were investigated. The Japan Highway Public Corporation conducted the same kind of survey over a continuous 48-hour period at Tunnel F (Chuo Expressway) and Tunnel G (Tomei Expressway). Items investigated in these surveys included wind velocity in tunnel lanes, traffic volume (separated by large and small vehicles), as well as the objects of ventilation, i.e., soot transmittance rates and CO concentrations. Analysis of the results from the aforementioned survey items provided average emission volume μ for both soot and CO. From the percentage of large vehicles surveyed at the same time, per-vehicle emission volume was derived differently for large and small vehicles (Table 2.3).

2.2.3 Laboratory experiments

Since the volume of noxious emissions largely depends on the operating conditions of a vehicle, it is preferable to take measurements of vehicles when they were running. However, because it is difficult to take direct measurements of noxious gases emanating from moving vehicles, lab experiments were conducted with the chassis dynamometer shown in Figure 2.1.

In the lab experiments, conditions of speed, load, gradient, etc., were determined by the

revolution of rollers. The volume of noxious gases emitted by vehicles was obtained from the concentrations and exhaust gas volume.

The running speeds for measurements were set constantly (40, 60, 80, and 100km/h). and all vehicles were tested at a gradient of 0%. In addition, there were six other gradients tested for 60km/h: -4, -2, (0), 2, 4, 6, and 8%. It should be noted that all vehicles used in the experiment, which are shown in Table 2.4, met the latest (1989) vehicle emission standards.

2.3. Research results

2.3.1 Summary of site survey

The results of analysis of soot emissions in the condition survey are shown in Table 2.5. It should be noted that soot emissions were corrected with the speed gradient and altitude correction coefficients and transformed to the value of 0% gradient and 0m altitude. It is thought that since Tunnel D had been newly built at the time of the survey, there was very little effect from sand brought into the tunnel, floating dust particles, wear-and-tear, etc., thus measured values of soot were smaller. In addition, since few large vehicles pass through Tunnel H because tunnel is located on the radial road in the city, because the tunnel forks off into different directions, the result of Tunnel H is probably a little bit eccentric. Thus the data of Tunnel D and H are omitted for the further analysis. The values for the rest of the tunnels are believed to be much smaller than present technological standards of the current ventilation edition (see Tables 2.1 and 2.2).

2.3.2 Summary of laboratory experiments

Soot is usually emitted due to incomplete combustion of fuels. The proportion of soot emissions is a function of engine air intake and fuel weight.

Since air intake of diesel engines is nearly constant for any stroke capacity, the emission of soot can be said to be a function of the volume of supplied fuel. However, engine output is also a function of the volume of supplied fuel. Therefore, it can be said that soot emissions per stroke capacity are a function of horsepower and are not dependent on engine size. With this in mind, the volume of soot emissions was estimated from the relation between soot and horsepower. Figure 2.3 shows the relation between soot emissions and running horsepower per unit volume for three types of engines: indirect injection (IDI), direct injection (non-supercharged) and direct injection (supercharged). The figure juxtaposes a regression formula derived from the least squares method and its standard deviation. This helps us to understand soot emissions caused both by combustion methods and the presence or lack of supercharging within roughly the same framework.

2.4. Volume of soot emissions

The volume of soot emissions was determined based on the results of the condition survey shown in Table 2.5. Previously, soot emissions had been expressed by the soot concentrations, and

volumetric exhaust emissions of diesel and gasoline vehicles each, but in this study, concentrations and volumetric exhaust emissions each are multiplied together to establish soot emission for large and small size vehicles. All items used to derive average values and standard deviations for soot emissions for large and small size vehicles, respectively, are shown in Table 2.6. It should be noted that, as mentioned in Section 3.1, the data from tunnels D and H were not suitable, so they were omitted from this Table. Because the values for soot emissions vary widely, the standard deviation is taken into account even in ventilation design. Therefore, when determining average soot emissions and standard deviations here, these variances had to be considered. Twice the value of the standard deviation was then added to the average soot value to derive the values for large and small size vehicles shown in Table 2.7. Since the values of present standards (the products in Table 2.1 and 2.2) and the values shown in Table 2.7 differ in vehicle type such as size or power they cannot be compared unconditionally, but if we consider that most large size vehicles are diesel powered, we can see that soot emissions are greatly decreasing. Most small size vehicles are gasoline powered. When we consider the increase in the percentage of diesel passenger cars, the values are only a little above those of present standards and are therefore quite reasonable.

2.5. Correction coefficient for speed and gradient

The speed and gradient coefficients are determined based on the relation between soot emission volume and running horsepower per unit emission volume of the laboratory experiments (see Table 2.3). In most cases, running horsepower was determined by vehicle speed and running resistance. Since running resistance is determined by the operation and use conditions of a vehicle (e.g., vehicle speed, longitudinal gradient), we can calculate the volume of soot emissions for vehicle operation at random speeds and longitudinal gradients from the relation between soot emissions and horsepower.

Figure 2.4 shows the soot correction coefficient for each type of engine at 60km/h. Here we can see that as gradient increases, soot emissions also increase.

It is the recent tendency that automobiles have been becoming bigger, that turbocharged engines are coming into greater use, and that soot emissions from gasoline vehicles are becoming negligible. However, since the results from our survey show that the soot correction coefficient for non-turbocharged vehicles is greater than that for turbocharged engines, we decided to derive a speed and gradient correction coefficient based on the 10t non-turbocharged vehicles in Fig. 2.4.

The correction coefficient for speed and gradient provides average soot emission values for each speed and gradient and then it leads, unit standard ventilation volume for the soot emission. Since it was assumed that few drivers suppress vehicle speed when traveling on a down slope, vehicle speed was adjusted to 60km/h for down slope.

Figure 2.5 shows the results for the above. Here we can see that as gradient and speed increased, the volume of necessary fresh air increased, and vice versa. In previous studies, there were differences in speed and gradient correction coefficients for vehicle speeds of 40-60km/h and 80km/h, even at a 0% gradient. However, no such difference was seen in this experiment. This is likely due to improved efficiency in vehicle design over the years, i.e., changing speeds under normal driving conditions has almost no effect on the volume of soot emissions.

2.6. Altitude correction coefficient

The emission volume for tunnels at high elevations (i.e., Tunnel B and F) were transformed to soot emissions at 0 gradient with the speed and gradient correction coefficient. Then the unit standard ventilation volume was calculated for this soot emission. Then the altitude correction coefficient was derived from this unit standard ventilation volumes. The results obtained in this research and the conventional altitude correction coefficient are shown in Figure 2.6. Here we can see that the altitude correction coefficient obtained for Tunnel F is roughly the same value as the current standards, while the value for Tunnel B is slightly higher. Though it was possible to recalculate the altitude correction coefficient from the results of these experiments, we were not able to derive a correction coefficient of sufficient accuracy because of the wide variance in the condition survey results, the small number of measuring points used in this survey, and other factors. Therefore, we have come to the conclusion that it is probably suitable for the time being to use the current standard values.

2.7. Response to future enlargement of the vehicle size

We investigated how future soot emissions might be affected by increases in vehicle size. We had to consider both changes in the proportions of the vehicle number of each of vehicle size and the changes of soot emissions attributed to enlargement of the vehicle size.

Future per-vehicle soot emissions attributable to enlargement of the vehicle size were calculated from target values for future allowable soot emissions established by the Report of the Central Pollution Policy Committee. In addition, the proportions of the vehicle member of each of vehicle size were estimated from both estimates of future ratios of operable vehicles and trends toward larger vehicles. As a result, the soot emissions attributable to enlargement of the vehicle size will show a slight increase over the emission values established here, but tougher regulation of conventional vehicles is expected to reduce soot emissions; hence, it is believed that over the coming years, soot emissions will decline and that the values for soot emissions in Table 2.7 give the safer standards.

2.8. Conclusion

2.8.1 Soot emissions

The proposed volume of soot emissions, as shown in Table 2.7, was derived from the results of ventilation surveys, (indirect method). Here, the values for large vehicles have declined considerably, while the values for small vehicles reflect the recent increasing proportion of small diesel automobiles on the road.

2.8.2 Speed and gradient correction coefficient

The speed and gradient correction coefficient was derived from direct measurements taken in laboratory experiments. As a result, we could obtain the curve shown in Figure 2.5. This curve was unaffected by vehicle speed at a gradient of 0%, and we could see that as gradient increased, so did the correction coefficient.

2.8.3 Altitude correction coefficient

The suitability of the altitude correction coefficient was investigated through the results of the condition survey. As a result, we could little difference between these values and those of the current standards.

2.9. Postscript

From the results of this study, we made the conclusions outlined in 8.1-8.3, which we believe can be used in future ventilation design. We also believe that promoting similar studies of future CO emissions will help to make ventilation design more efficient and effective. Finally, we would like to thank the various public corporations and road administrations for their cooperation and assistance.

Table 2.1 Present base values for soot concentrations in exhaust gas

Vehicle type	Avg. value μ (1/m)	Std. deviation σ (1/m)
Diesel	0.6	0.5
Gasoline	0.05	0.0

Table 2.2 Present average exhaust gas volume

Vehicle type	Avg. exhaust volume $V(m^3/km)$
Diesel	5.6
Gasoline	1.3

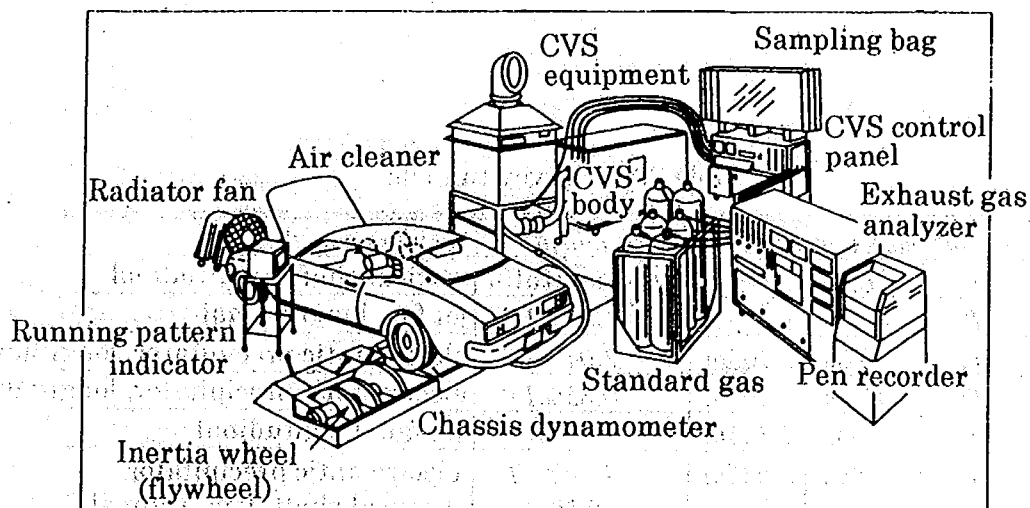


Figure 2.1 Test chassis dynamometer

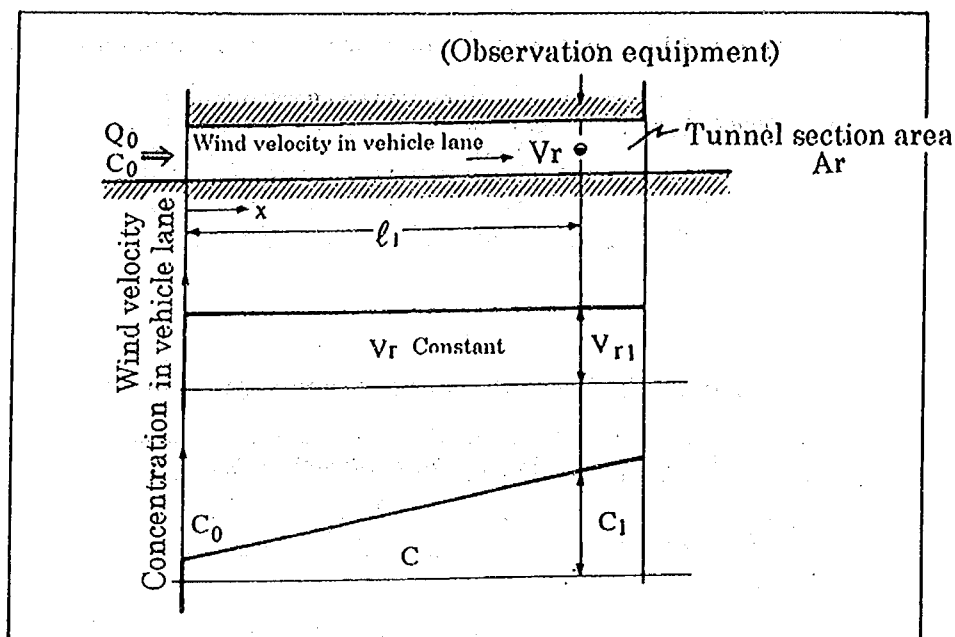


Figure 2.2 Outline of longitudinal ventilation method

Table 2.3 Survey tunnels

Tunnel	elevation	length	gradient	ventilation method
A	66m	844m	two-way traffic	vertical shaft, longitudinal
B	822m	1,450m	1.05%TT	jet fan, longitudinal
C	57m	2,200m	2.04%TT	electrostatic precipitator, longitudinal
D	104m	2,201m	0.85%TT	electrostatic precipitator, longitudinal
E	89m	1,125m	1.15%TT	jet fan, longitudinal
F	700m	8,625m	1.84%TT 0.5%AT	electrostatic precipitator vertical shaft, longitudinal
G	150m	1,539m	1.4%TT 0.5%AT	jet fan, longitudinal
H	87m	3,032m	3.45%TT	vertical shaft, longitudinal

(note: TT= heading toward Tokyo; AT= heading away from Tokyo)

Table 2.4 Test vehicles

Type	Load class	Engine type
Diesel trucks	2ton	IDI-NA
		DI-TC
	4ton	DI-NA
		DI-TC
	10ton	DI-NA
		DI-TC

IDI: Indirect injection diesel

DI: Direct injection diesel (chamber)

NA: Natural aspirate

TC: Turbocharged

Table 2.5 Soot emissions from the condition survey

Tunnel	Soot emissions (large veh) (m ² /veh.km)		Soot emissions (small veh) (m ² /veh.km)	
	avg. value	std. deviation	avg. value	std. deviation
A	1.935	0.769	0.145	0.078
	1.719	0.668	0.109	0.000
B	2.033	0.410	0.186	0.191
C	1.890	0.507	0.043	0.052
D	1.015	0.089	0.209	0.190
E	1.640	0.448	0.008	0.001
F	1.860	0.739	0.023	0.262
	1.850	0.971	0.148	0.254
G	2.273	-	-	-
H	0.572	0.287	0.018	0.027

Table 2.6 Average values and standard deviations from the condition survey

Vehicle type	Soot emissions (average)		Soot emissions (standard deviation)	
	Avg. value ($m^3/veh \cdot km$)	Std. deviation ($m^3/veh \cdot km$)	Avg. value ($m^3/veh \cdot km$)	Std. deviation ($m^3/veh \cdot km$)
Large	1.900	0.181	0.645	0.187
Small	0.095	0.065	0.120	0.106

Table 2.7 Proposed values for soot emissions

Vehicle type	Avg. value μ ($m^3/veh \cdot km$)	Std. deviation σ ($m^3/veh \cdot km$)
Large	2.2	1.0
Small	0.2	0.3

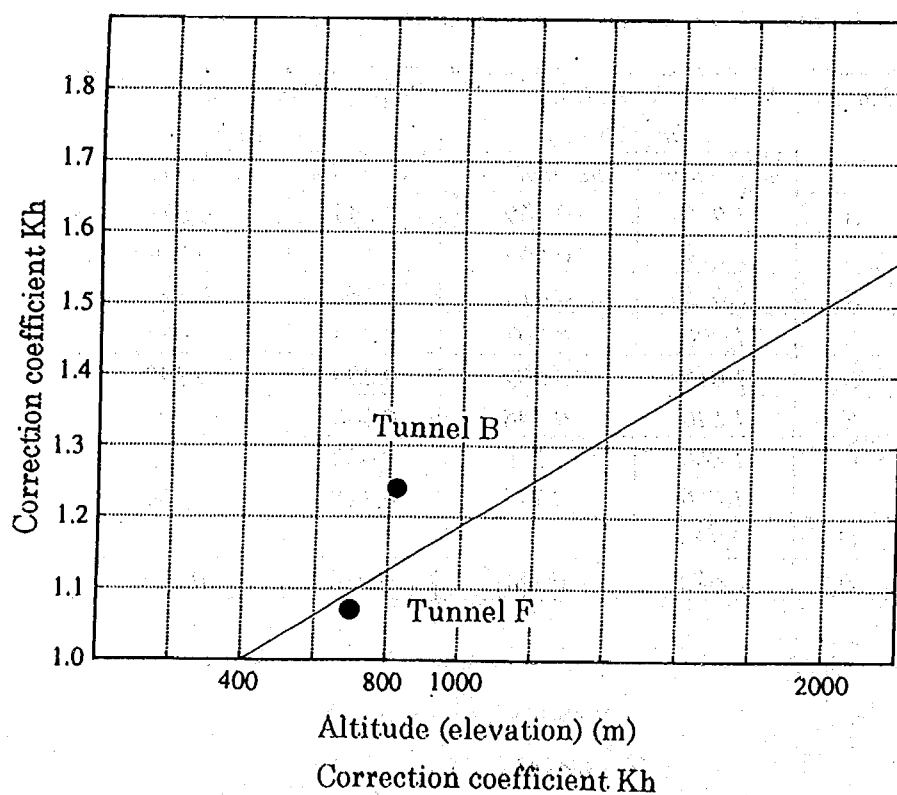


Figure 2.6 Altitude correction coefficient and the measured values

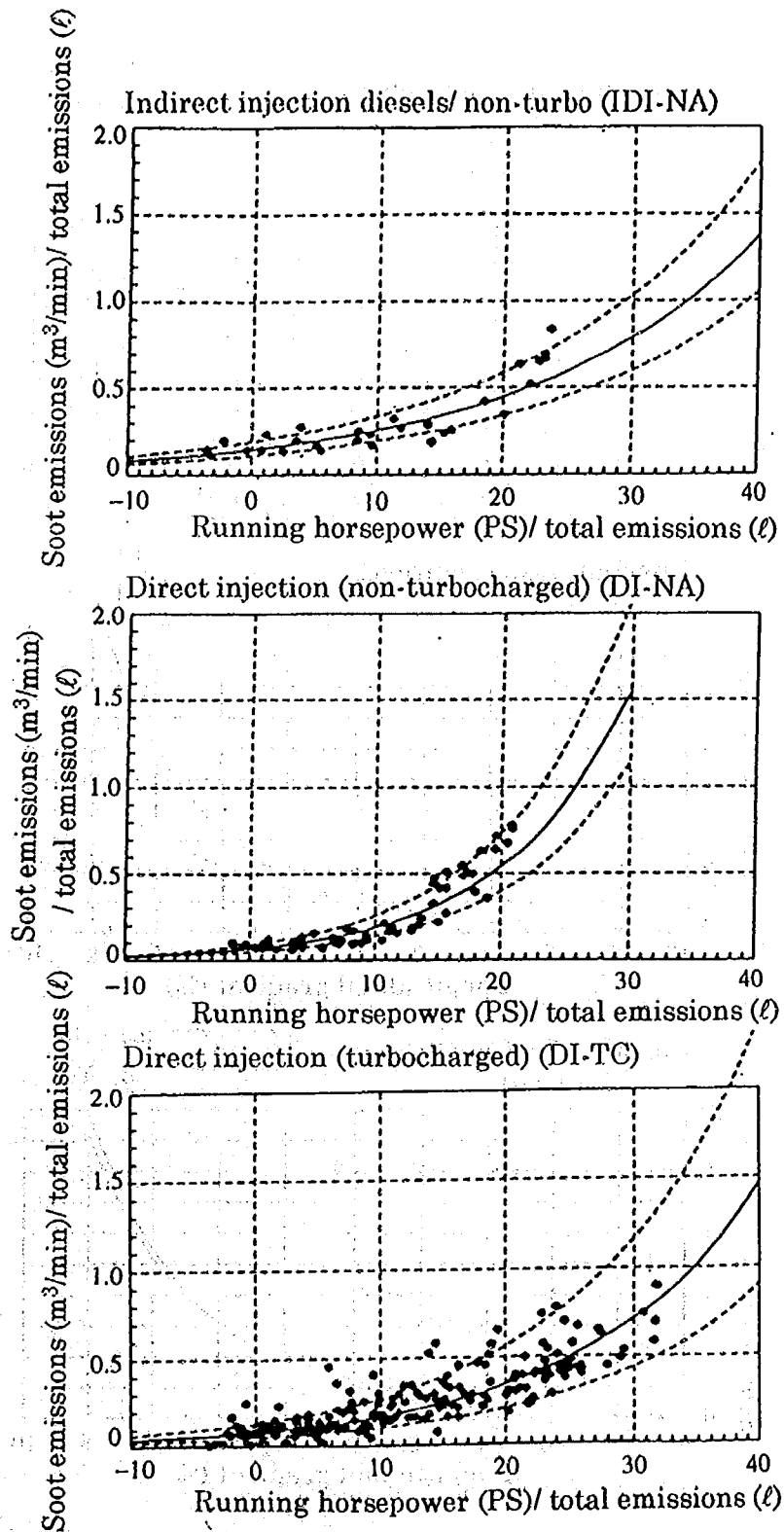


Figure 2.3 Relation between soot emissions and horsepower, per unit emission

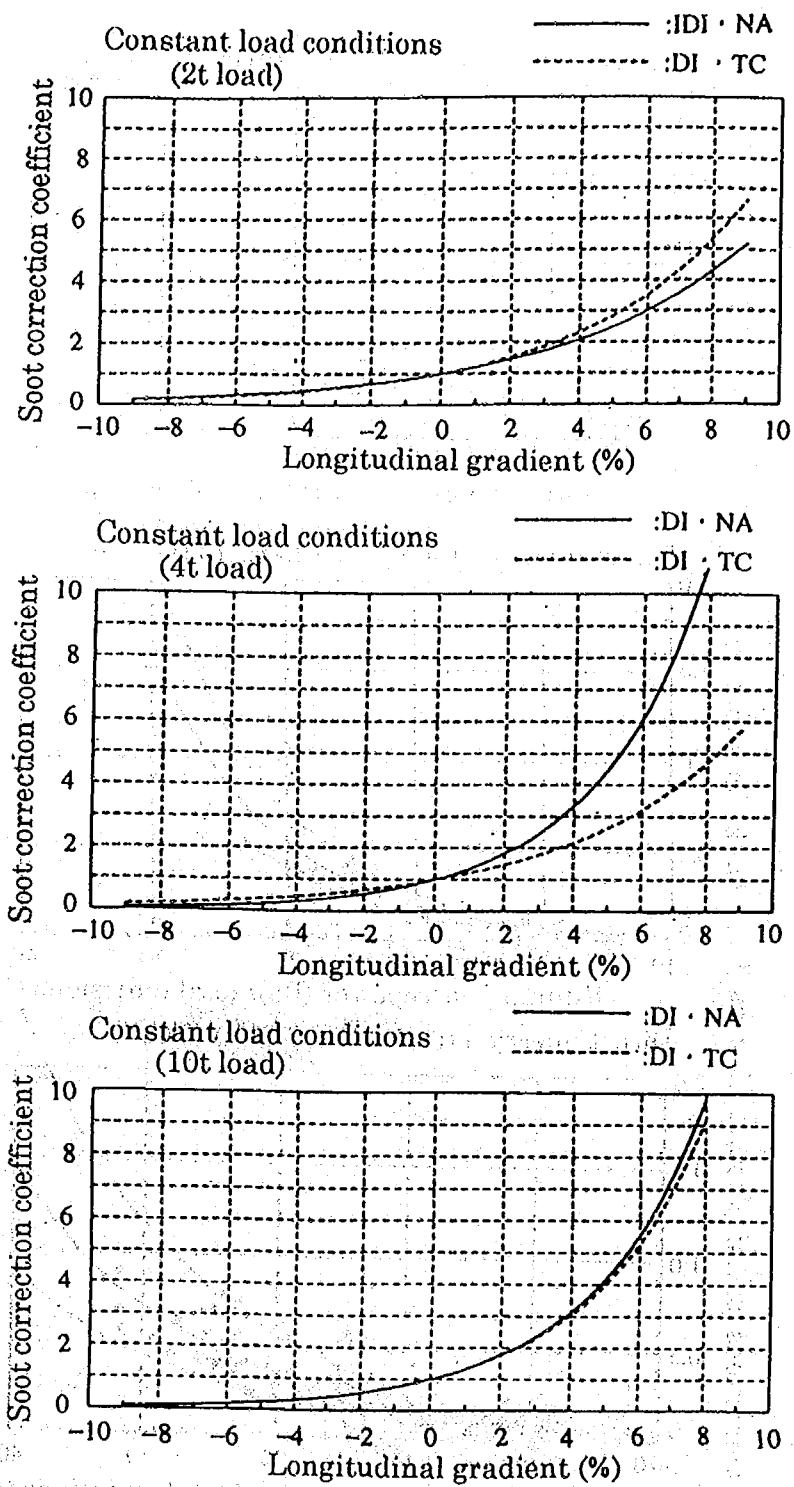


Figure 2.4 The measured results on gradient correction coefficients for soot emissions

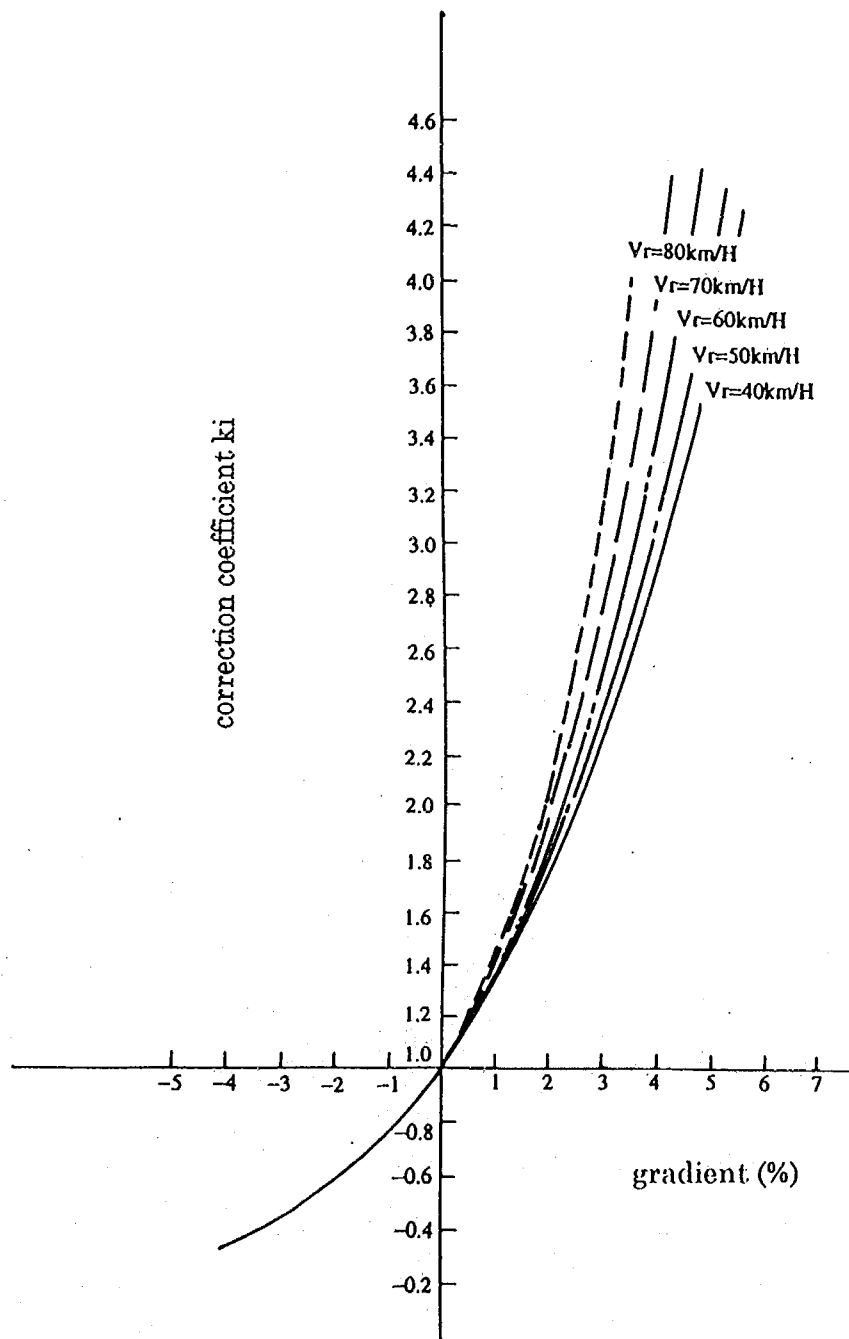


Figure 2.5 Proposed speed and gradient correction coefficient

Research on New Road Tunnel
Lighting and Soot Emission
for Ventilation Design

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Synopsis

This report shows the state of the road tunnel equipment technology in Japan. The contents are based on the published materials and the recent data from the tunnels in public use. Chapter 1 shows the general affairs of road tunnels and tunneling technology in Japan. Chapter 2, 3, 4 discuss road tunnel ventilation, road tunnel lighting and road tunnel safety technology respectively.

Key Words: tunnel equipment, ventilation, lighting, safety

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