EFFECTS OF CONTRIBUTING TO DECARBONIZATION BY MODEL-BASED PREDICTIVE VENTILATION CONTROL (MPVC) ON EXPRESSWAYS

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ABSTRACT

Although the scale of ventilation in highway tunnels has been decreasing due to stricter exhaust gas regulations, normal ventilation is still required under special conditions, such as long tunnels with two-way traffic and tunnels that require environmental measures at the portal. Historically, achieving stable, effective ventilation control in such complex tunnels without wasteful power consumption has been an issue. To address this, the NEXCO Research Institute and NEXCO companies have introduced the tunnel ventilation control software MPVC, which performs optimal control Based on a survey of the operational status of tunnels where MPVC has been introduced, this paper evaluates the optimization of control and the effect of reducing power consumption, and clarifies the contribution to decarbonization, future issues, and prospects.

Keywords: MPVC, Tunnel ventilation control, Decarbonization, Predictive control, Power consumption

1. INTRODUCTION

The amount of soot and other such pollutants exhausted by vehicles has decreased significantly thanks to stricter exhaust gas regulations. Currently, optimising emergency tunnel ventilation in the event of fire has become the mainstream. Nevertheless, tunnels under special conditions, such as long tunnels with two-way traffic and urban tunnels that need environmental measures at the portal, still require normal ventilation. Controlling ventilation in such tunnels is challenging, and unless controlled efficiently, power consumption will be high. For this reason, NEXCO Research Institute and the three NEXCO companies have introduced and are operating tunnel ventilation software MPVC (Model-based Predictive Ventilation Control) since 2007. [3],[4],[5] This software allows an accurate prediction of the ventilation status in the tunnel through multiple real-time simulations and provides an optimal control to reduce the amount of electricity for fans while maintaining various control values.
This paper investigates the actual operational status of tunnel ventilation where MPVC is introduced, evaluates the optimization of ventilation control and the reduction of power

consumption, and also describes the effects of MPVC, including its contribution to decarbonization. In addition, issues extracted from the investigation are summarized and prospects of future tunnel ventilation are also mentioned.

2. CONVENTIONAL VENTILATION CONTROL

Tunnel ventilation must be controlled so that jet fans, exhaust fans and other such equipment, installed to prevent air pollution caused by automobile exhaust gas, are operated while maintaining various control values to avoid excessive power consumption. Conventional control methods adopted in Japan are mainly classified into the following three types.

2.1. FB (Feed Back) control

This method operates fans by comparing measured VI (Visibility Index) and CO levels against target values. Because operation only triggers after levels reach the target, rapid air quality deterioration can lead to recovery delays. Its simplicity, while reliable, can result in operational inefficiency.

2.2. FF (Feed Forward) control

This method determines fan output by predicting future tunnel conditions based on upstream traffic data. While potentially more efficient, any discrepancy between predictions and actual traffic can lead to unnecessary energy use or deviations from target environmental values.

2.3. AI Fuzzy control

This approach combines FB and FF methods to mitigate their respective weaknesses. Although Fuzzy theory aimed to improve prediction accuracy, adjusting fluctuating parameters (like soot volume) proved difficult. Unlike modern data-driven AI, this "expert system" relies on manual IF-THEN rules and specialized technical knowledge.

3. OVERVIEW & CHARACTERISTICS OF MPVC

3.1. Overview

The MPVC, a solution to cope with the issues facing conventional ventilation control, simulates and predicts conditions inside the tunnel using traffic data from traffic counters and data from other measurement instruments inside the tunnel to best control ventilation. In addition, it automatically corrects various parameters by comparing the predicted and actually measured values, and then applies the corrected parameters to the next calculation to repeatedly improve them. This ventilation control software has been installed and operated in tunnels in Japan since 2007. The followings describe the operation flow of MPVC (Figure 1).

1) Predict traffic flow inside the tunnel for a certain later time period from the traffic volume of each large and small vehicles measured by a traffic counters. (Traffic simulation)
2) Create combinations of all fans that can be transitioned, considering the situation of fans operating at the time of control.
3) Based on the predicted traffic flow, compute post-operation target control values (VI/CO, etc.) for all fan combinations. (Ventilation simulation)

4) Select the combination that satisfies the target control value and consumes least power from all of the results, and give instructions for ventilation control.
5) Lastly, compare traffic simulation values and ventilation simulation values to actually measured values, and correct parameters. (Traffic reconciliation, ventilation reconciliation)

3.2. Simulation in real time

As a result of real-time simulations, the graph shown in Figure 2 is created in the work processes 2 to 4. This graph is a comparison of power consumption of multiple, simulated fan combinations in post-control tunnel environment simulations created based on actual tunnel conditions. In the graph, those that have satisfied the control target are coloured. In other words, next time, the operation order will be to carry out the combination with the least power consumption among the coloured ones. In addition, the next control instruction also implements control to suppress sudden changes in ventilation machine operation. The idea of simulating, analysing, and predicting in virtual space is exactly the same as modern digital twin technology, and the fact that it was already implemented some 20 years ago means the technology was pioneering.

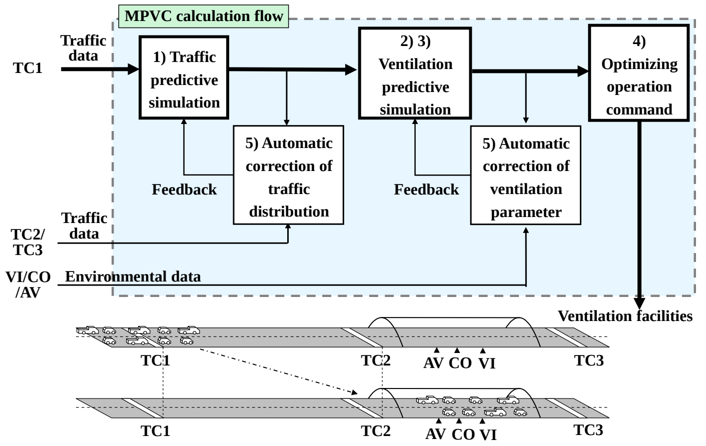

Figure 1: MPVC system flow diagram in the model tunnel

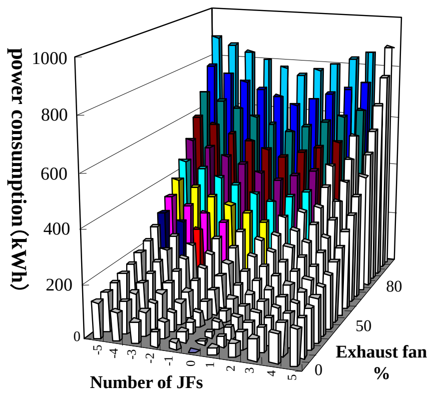

Figure 2: Ventilation combination and power consumption

3.3. Auto-correction of parameters

Parameters for forecasting ventilation fluctuate. These parameters, such as emission coefficients of automobile exhaust gas, which is decreasing year by year, and front projection area that differ per vehicle, are automatically corrected. Conventional AI fuzzy control and the like do not have this function, and parameters were changed manually after analysing the data and verifying them when necessary. This took time, but MPVC automatically corrects them in real-time.[6],[7]

4. POWER CONSUMPTION OF MPVC INTRODUCED TUNNELS

Currently there are about 2,000 tunnel tubes operated by East, Central and West NEXCO companies. Of them some 300 tubes are equipped with ventilation facilities, the majority of which are designed for smoke exhaust, as this has become the mainstream solution in the event of fire. MPVC is effective in long two-way tunnels, urban tunnels requiring environmental measures at the portals and other tunnels where controlling ventilation to meet their special conditions is complicated. At the present, the three NEXCO companies have introduced and are operating 12 systems in 23 tubes (Table 1).

The annual power consumption on expressways operated by the three NEXCO companies is 1,143,095MWh (2023 results), of which some 22,406MWh, 2 % of the total, is consumed by ventilation equipment (Figure 3). In addition, the power consumption of tunnels with MPVC is 12,891MWh, which means more than half of the power consumed by ventilation is controlled by MPVC (Figure 4).

Compared with the power consumption in 2003, before the introduction of MPVC, the total power consumption has decreased, even though the extension of expressways in service has increased in the intervening 20 years. Looking at the breakdown, the share of consumption by lightings and ventilation equipment has decreased (The annual power consumption of tunnel ventilation decreased about 70% in 20 years.). Lightings switched to LED, more efficiently controlled tunnel ventilation systems by MPVC, and the review of design standards leading to lower automobile emissions are considered to be the factors for the reduction. NEXCO Research Institute has contributed to decarbonization by revising the design criteria.

Table 1: Tunnels with MPVC in Japanese Expressways

No.	Tunnel name	Traffic direction	Length [m]	Facilities	Control target
1	Oyubari	Two-way	4,213	JF×8	VI, CO & Humidity
	Kaede	Two-way	1,955	JF×3	VI & CO
	Osawa	Two-way	1,541	JF×3	VI & CO
	Hobetsu	Two-way	4,318	JF×9	VI & CO
	Shimukappu	Two-way	3,824	JF×7	VI & CO
2	Tenguyama	Two-way	2,978	JF×4	VI & CO
	Tenjin Second	Two-way	2,872	JF×4	VI & CO
3	Waga-sennin	Two-way	3,775	JF×4	VI & CO
4	Kan-etsu	One-way	11,055	Supply fan×6 / Exhaust fan×4	AV
5	Ome	One-way	2,062	JF×4 / Exhaust fan×2	VI, CO & AV
6	Tarutouge	Two-way	4,998	JF×11	VI, CO & Humidity
	Moriyama	Two-way	1,734	JF×4	VI & CO
	Tozurasawa	Two-way	2,295	JF×3	VI & CO
7	Hachioji-joseki	One-way	2,380	JF×4 / Exhaust fan×2	VI, CO & NOx
	Takaosan	One-way	1,329	JF×14 / Exhaust fan×2	VI, CO & NOx
8	Hida	Two-way	10,700	JF×15 / Exhaust fan×10	VI, CO & Humidity
9	Fujishiro [up]	One-way	1,805	JF×9 / Exhaust fan×2	VI, CO & SPM
	Fujishiro [down]	One-way	2,136	JF×2 / ESP×1	VI, CO & SPM
10	Shimotsu [up]	One-way	1,243	JF×7 / Exhaust fan×2	VI, CO & SPM
	Shimotsu [down]	One-way	1,287	ESP×1	VI, CO & SPM
11	Nagamine [up]	One-way	3,831	JF×3 / ESP×1	VI, CO & SPM
	Nagamine [down]	One-way	4,043	JF×3 / ESP×2	VI, CO & SPM
12	Kanmon	Two-way	3,461	Supply fan×8 / Exhaust fan×8	VI, CO & AV

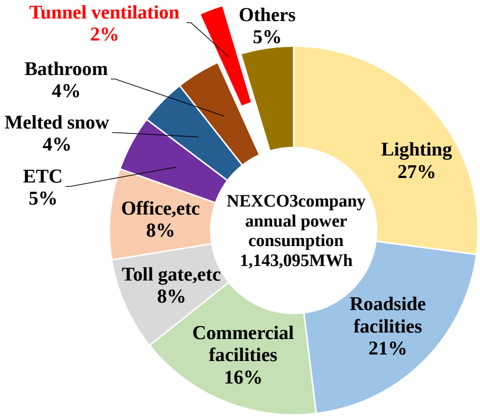

Figure 3: NEXCO 3 companies' annual power consumption usage breakdown in 2023

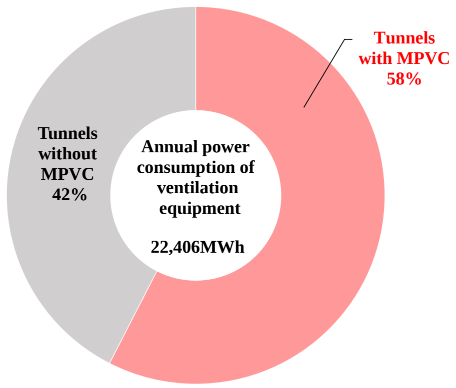

Figure 4: Breakdown of tunnel ventilation power consumption

5. EVALUATION OF MPVC

The 2023 log data on tunnels with MPVC were collected to the extent possible and various analyses have been carried out to evaluate the method.

5.1. Evaluation of ventilation control optimization

The purpose of controlling tunnel ventilation is to operate ventilation observing the tolerance and other values so that the tunnel interior and portal environment are optimized. To do that, the tolerance and actual values for each tunnel were evaluated. Figure 5 and Figure 6 show the actual VI and CO values of each tunnel in 2023. The results show that tolerance values are maintained throughout the year, i.e., MPVC controls ventilation so that the tunnel environment is maintained optimally. It was also confirmed that optimum tunnel outside portal environment was also maintained for SPM (Suspended Particulate Matter) targeted tunnel where the airflow velocity was the target value for controlling ventilation.

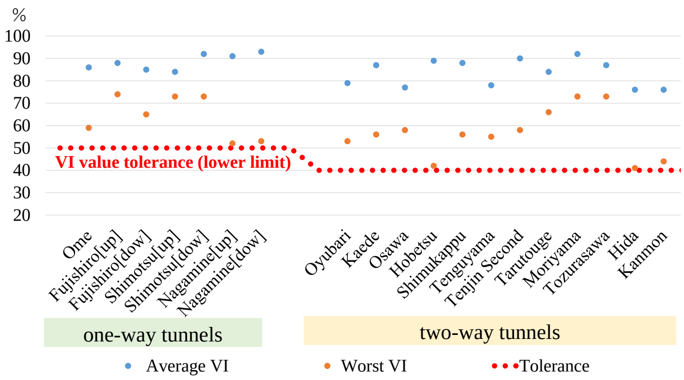

Figure 5: VI value

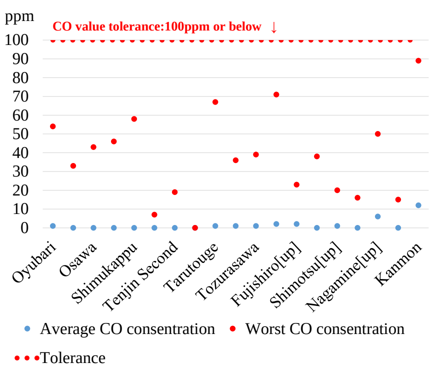

Figure 6: CO concentration

5.2. Evaluation of power consumption reduction

The purpose of MPVC is to optimize the tunnel environment with minimal power consumption. The optimization of ventilation control is guaranteed, as mentioned above, and the effect on the reduction of power consumption was evaluated on this premise. The evaluation was conducted in a tunnel where changes in power consumption can be seen before and after the introduction of MPVC (Table 2). As a result, 32% to 57% reduction was seen in each tunnel, and the total amount of reduction was about 30%. Based on this reduction amount, the cumulative CO2 reduction calculated from the time of MPVC introduction in each tunnel is approximately 8,000t. Assuming all tunnels with MPVC reduced 30% of their CO2 emissions, the cumulative CO2 reduction from the time of introduction is about 36,000t-CO2, which is equivalent to the amount of annual CO2 emitted by about 10,000 ordinary households in Japan.

Table 2: Annual power consumption reduction effect by MPVC

Tunnel name	Ventilation power consumption		Reduced power consumption [MWh]	Reduction rate
	Before MPVC introduce [MWh]	After MPVC introduce [MWh]		
Osawa & Hobetsu	101	43	58	57%
Shimukappu	61	29	32	52%
Kan-etsu	3,171	2,150	1,021	32%
Kanmon	2,241	1,527	714	32%

5.3. Focus on the specific MPVC

We took a close-up look at the actual state of controlling ventilation in tunnels with MPVC to evaluate the effects of MPVC for different ventilation systems. While there are several other MPVC applications, such as the Hida Tunnel [8], two representative cases are presented below.

5.3.1. Transversal ventilation control system (Kanmon Tunnel)

Figure 7 shows the ventilation system at Kanmon Tunnel. The tunnel is a two-way tunnel with a transversal ventilation system with 4 shafts. Ventilation is controlled to optimize VI/CO in the tunnel and also to simultaneously control wind speed so that it is maintained within ± 2.5m/s to obtain a rapid response in exhausting smoke. Figure 8 and Figure 9 compare daily ventilation trends in the Kanmon Tunnel on a day before and after the implementation of MPVC when traffic conditions were similar. Before the implementation of MPVC (hereinafter “old control”) controlling ventilation meant operating supply fans and exhaust fans of each shaft simultaneously, and the operation tended to be relatively continuous. On the other hand, after the introduction of MPVC (hereinafter “new control”), supply fans and exhaust fans are operated independently, and thus more finely, to reduce power consumption. As a result, though VI decreased in the morning and evening in the old control, the new control maintained a stable and good environment throughout the day. Power consumption was 3,946kWh for the old control, but it decreased 30% and was 2,713kWh for the new control.

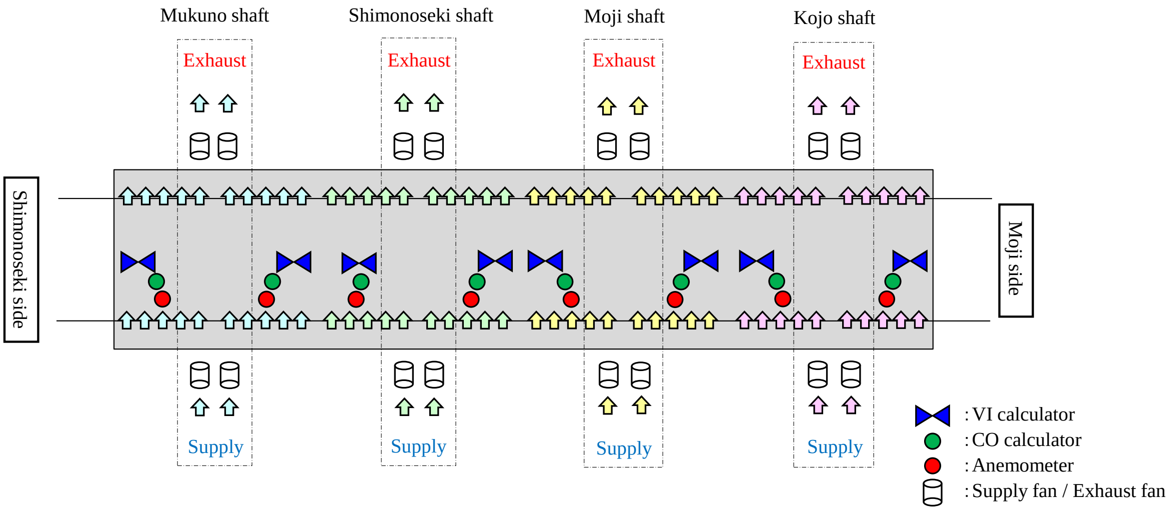

Figure 7: Kanmon Tunnel’s ventilation system diagram

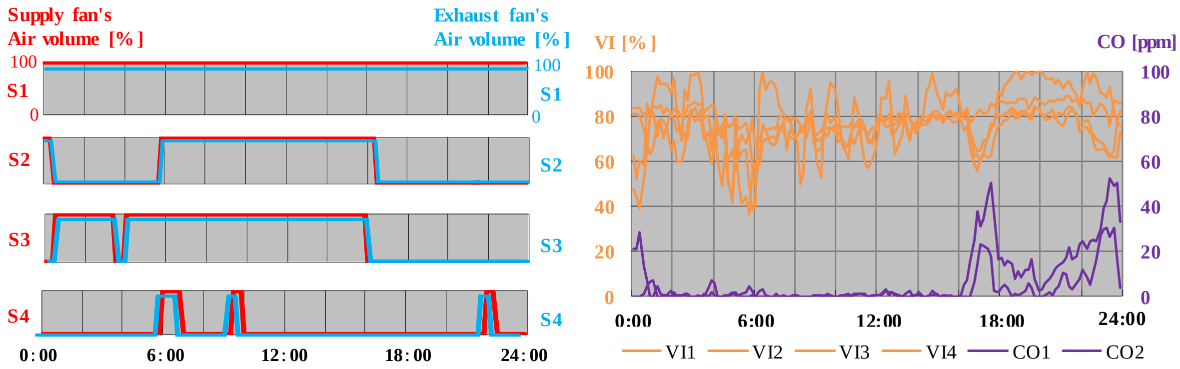

Figure 8: Ventilation trends without MPVC

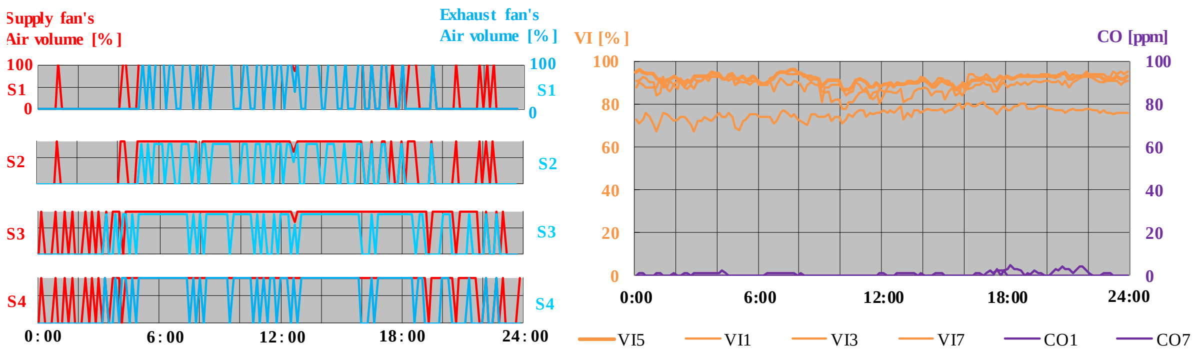

Figure 9: Ventilation trends with MPVC

5.3.2. Temperature & humidity ventilation control system (Oyubari Tunnel)

Figure 10 is the ventilation system at Oyubari Tunnel. The tunnel is a two-way tunnel with a longitudinal ventilation system operating 8 jet fans to control ventilation so that optimum VI/CO level is maintained. The tunnel is in one of the coldest regions in Japan and the relationship between the difference in the inside and outside temperature and saturated humidity may cause fog inside the tunnel in the winter, leading to poor visibility and vehicle windshields quickly fogging up. As a countermeasure, jet fans are operated to reduce the inside and outside temperature difference and prevent poor visibility.[9]

Figure 11 shows the trend of a day when jet fans were most heavily operated by this control method. By operating the jet fans when the outside and inside temperature difference is large and controlling ventilation so that outside air flows in, the temperature difference which was 20°C or more lowered to a daily average of about 2°C (Figure 11). As a result, the VI values were stabilized and poor visibility did not occur, as shown in Figure 12. In addition, MPVC maintains a small, controlled fluctuation in the temperature difference between the inside and outside of the tunnel, thereby preventing poor visibility caused by large temperature differences.

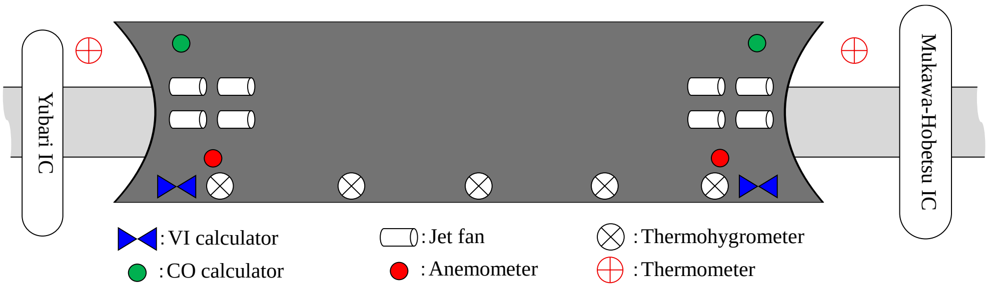

Figure 10: Oyubari Tunnel's ventilation system diagram

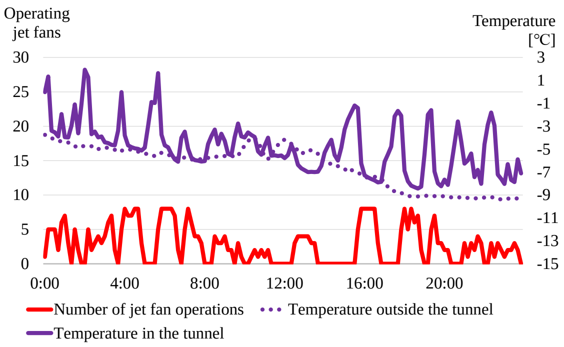

Figure 11: Temperatures inside and outside the tunnel and jet fan operation

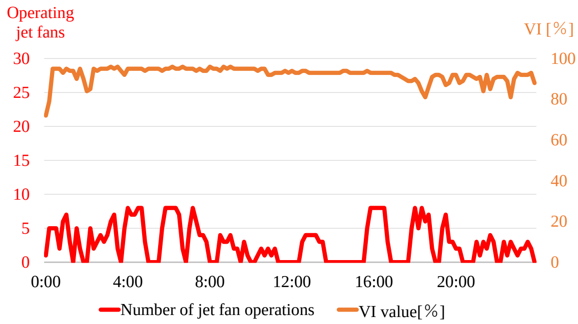

Figure 12: Jet fan operation trend and VI value

5.4. Consideration of auto-corrected parameters

Automatic parameter correction, a feature of MPVC, is aimed at improving prediction accuracy. Nevertheless, it was found that there are differences between the corrected values of each tunnel and the design ventilation values. Table 3 shows the difference between the average value of the log data correction and the current design guideline values. It can be seen that vehicle equivalent resistance area and soot, smoke and CO emissions values are less than those in the design criteria. We consider that MPVC cannot only control ventilation but also has the potential to sense and evaluate ventilation design values.

Table 3: The actual situation of auto-corrected parameters

Parameter	Automobile equivalent area [m^2]		Soot and smoke emissions [m^2/km・number]		CO emissions [m^2/km・number]	
	Large	Small	Large	Small	Large	Small
Design specification value	6.88	2.45	0.66	0.23	0.003	0.003
The above value corrected by the average compensation value	5.60	2.14	0.55	0.18	0.002	0.001
Auto-correction reference difference	-1.277	-0.313	-0.113	-0.049	-0.001	-0.002

6. CONCLUSION

Some 20 years have passed since MPVC was first introduced in Japanese tunnels. This was the first time that we have evaluated and verified the software by collecting annual logs comprehensively. Although power consumption by tunnel ventilation systems for the entire road network is decreasing, MPVC has been introduced for the purpose of efficient ventilation control in tunnels where complex ventilation control is required. From the results of our

verification, it has once again become clear that MPVC is an excellent ventilation control software that contributes to decarbonization by achieving both accurate ventilation and reduction in power consumption by 30% (estimated cumulative CO_2 reduction: approx. 36,000t). Furthermore, by using MPVC's auto-parameter correction function, it is thought that the values of the design criteria may be evaluated and the data that are more in line with the actual situation be applied in the revisions of the guidelines.
A future issue is that because the log data required for evaluation and verification are stored at the site of each tunnel, it takes a lot of work to collect the data, and therefore, cannot be used in real-time. To counter this issue, it is necessary to systematize constant monitoring of logs to save labour and conduct regular evaluation and verification.
Controlling ventilation is expected to become even more complicated in tunnels where MPVC is scheduled to be introduced. But we would like to make use of what we have learned from the evaluation and verification this time so that we may contribute to decarbonization and optimization of road management.

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