# Three Dimensional Characteristics of the Airflow in Unidirectional Vehicle Tunnels

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## Abstract

Airflow distributions along tunnel and over the cross section are critical in selecting installation location of the velocity monitor to obtain the representative data for ventilation as well as fire safety systems. This paper aims at performing CFD and on-site studies to analyze the longitudinal and cross-sectional distributions of the air velocity in tunnels employing longitudinal and semi-transversal ventilation systems. This study can ultimately contribute to selecting the monitor type as well as the optimal installation locations in vehicle tunnel.

## 1. INTRODUCTION

Since typical flow patterns observed in unidirectional vehicle tunnels are transient pseudo-steady state flow fluctuating due to traffic speed and volumes, airflow distribution does not seem to be uniform along the tunnel axis as well as over the cross section. In most of the cases it is mandatory to have the velocity monitors installed for measuring the airflow direction and velocity. The measurements are critical in controlling airflow rate and subsequently pollution level inside the tunnels, while the data from monitors are essential in securing the airflow velocity to prevent the backlayering phenomenon in case of a tunnel fire. Therefore, the monitors should provide accurate representative values over the cross section. The monitors are usually installed to obtain the air velocities measured either over the line across the cross section or at a fixed location close to the tunnel wall. To find an appropriate location for the airflow monitor and measure the accurate representative velocity data, it is required to understand the three dimensional airflow distribution in tunnels.

This paper aims at analyzing the airflow distribution along the axis and over the cross section through the CFD method as well as the on-site studies.

## 2. CFD Analysis

Selection of the monitor location along the tunnel axis is affected by the jet stream generated by the jet fan. Its influence should be avoided since the measurements are likely to be deviated from the representativeness. FLUENT is applied to the model tunnel described in Table 1. As shown, 8 jet fans are installed at intervals of 180 meters with two fans on the same cross section. The jet fans have specifications found in typical tunnel ventilation and smoke extraction fans.

Table 1. The Target Tunnel Description

| Category | | Description |
|---|---|---|
| Length | | 1000m |
| Width and Height | | 10.8m, 6.4m |
| Jet fans | Specifications | Φ1030, discharge velocity: 30m/s |
| | Installation | 8 fans, 4 locations, 2 fans at the same cross section, installation interval: 180m |

The following Fig. 1 shows the flow velocities along the tunnel over the cross section cut at the height of 3.4m parallel to the road surface. Cross-sectional patterns near the wall vary with the distance from jet fans and become uniform at approximately 145 meters downstream, while axial distribution reaches uniformity at about 200 meters from fans.

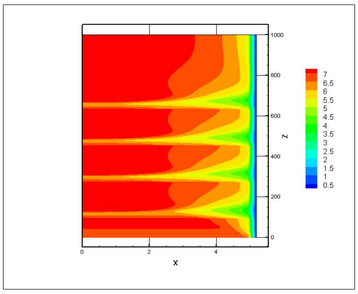
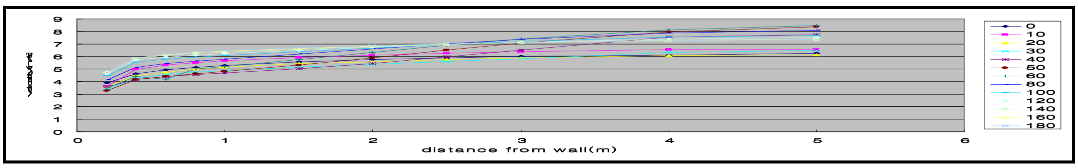
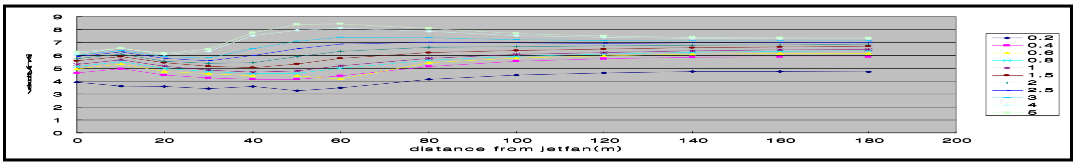


Fig. 1 Air flow Distribution along the Tunnel during Jet Fan Operation

Fig. 2-a delineates the results against the distance from the wall, while Fig. 2-b arranges the same output against the distance from the fans. The figures show that once the airflow reaches beyond 140m downstream of the fans and out of the influence of jet stream, the air velocity does not change significantly; it varies within 1m/s in the range of 40cm to 2.5m from the wall.




a. Velocity against the Distance from the Wall




b. Velocity against the Distance from the Jet Fans

Fig. 2 Velocity Variation from the Wall over the Cross Section

A cross section cut vertically at distance of 30cm from the wall and at height of 3.4m is shown in Fig. 3. Fig. 4-a shows velocities along the height, while velocity variation with the distance from fans is displayed in Fig. 4-b. Even though air velocity varies considerably with the height, velocity remains almost constant in the range of 0.6 and 3.6m from the bottom. Also it shows that velocity distribution near the wall becomes uniform beyond approximately 145m downstream of the jet fans.

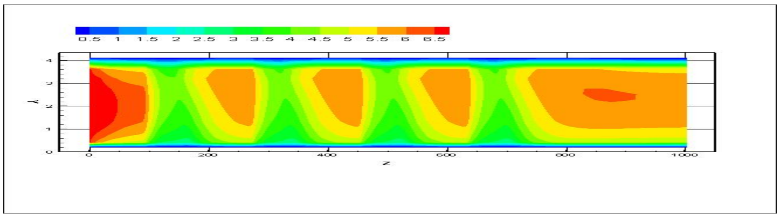
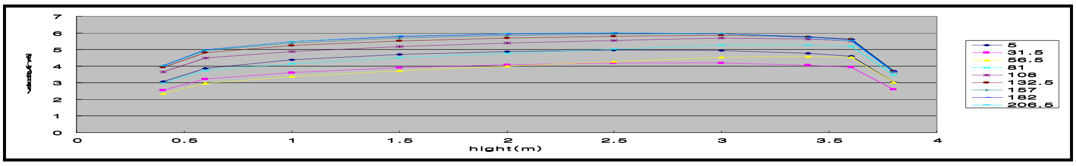
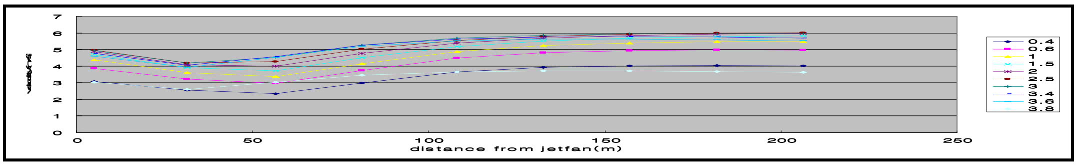


Fig. 3 Velocity Profile by Height



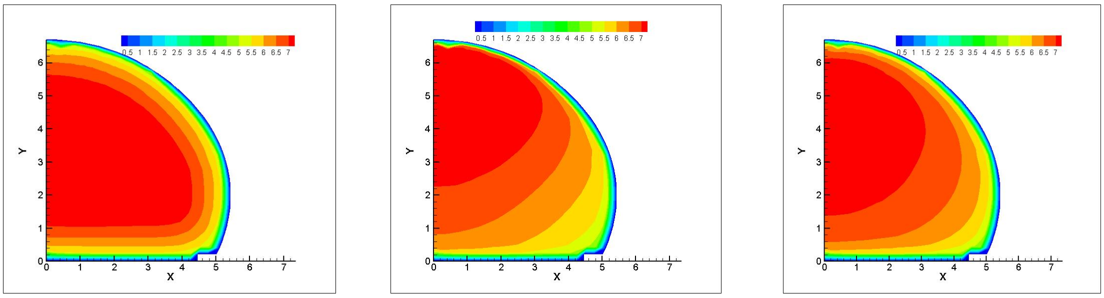

a. Variation by distance from the jet fans




b. Variation by distance from the wall

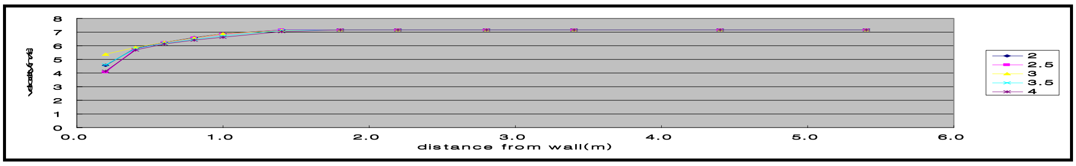
Fig. 4 Velocity variation with height

Fig. 5-a, b and c include the velocity profiles at 27m upstream, 145m downstream and 197m downstream of the jet fans. Zones with higher velocities are more or less centered in case of the upstream location.

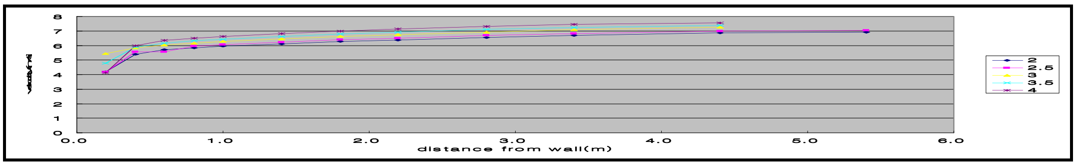


a. 27m upstream b. 145m downstream c. 197m downstream

Fig. 5 Velocity Profiles by Distance from the Jet fans




a. 27m upstream




b. 145m downstream

Fig. 6 Near-Wall Velocity Variation by Height

Fig. 5-a and b summarize the velocity variation by the distance from the wall on the vertical plane. These results confirm the previous findings which were depicted in Fig. 4. Therefore, it is concluded that regardless of height above the road surface, the air velocity varies insignificantly in the range of 0.4 to 2m from the wall. In the tunnels open to traffic, outside this range toward the center the velocity is almost constant over the cross section due to the moving vehicles.

## 3. On-Site Study

A series of studies had been carried out at five different tunnels whose descriptions are made in Table 2. The experiment was designed to study the three directional velocity variation with two 3-D velocity monitors, while measurements by ultrasonic velocity meters in tunnels were used for comparison purpose and traffic data were provided by the tunnel operators.

Table 2. On-site Study Tunnels

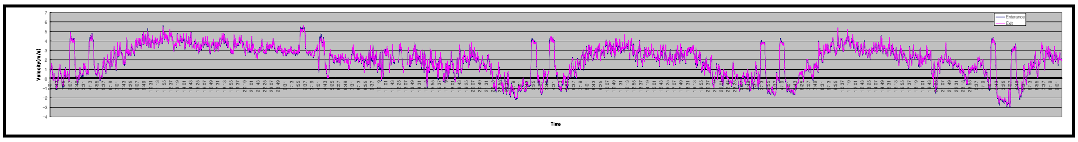
| Tunnel | Type | Length (m) | Installation Locations for the | | | | Ventilation system |
|---|---|---|---|---|---|---|---|
| | | | Case 1 | | Case 2 | | |
| Jangsung | Highway | 3450 | 668 | 3200 | * | | Longitudinal (jet fan) |
| Pibanryong | Highway | 2040 | 100 | 1940 | * | | Longitudinal (jet fan) |
| Sujungsan | Urban | 2356 | 400 | 1956 | 900 | 1456 | Longitudinal (EP, jet fan) |
| Baekyangsan | Urban | 2340 | 300 | 2040 | 800 | 1240 | Semi-transverse |
| Imgo-4 | Highway | 1667 | 780 | | * | | Longitudinal (jet fan) |

## 3.1 Variation along the tunnel

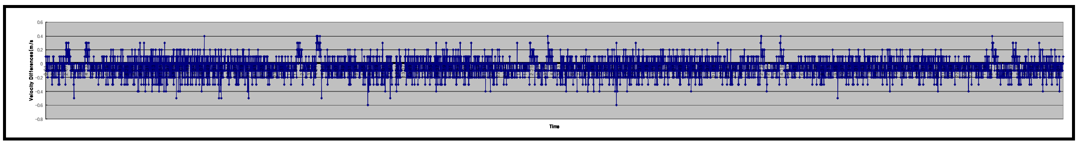
In most of the long tunnels, two locations, usually one near the entrance and the other near the exit portal, are selected for velocity meters. Discrepancy between their measurements can generate serious results in case of a fire. To prevent the backlayering phenomenon, representative data have to be monitored from the meters. In this study, two velocity monitors were installed at the locations described in Table 2. Two sets of experiments were performed with one at 20% and 80% of the tunnel length and the other at 30% and 60%.

**A. Jangsung Tunnel**

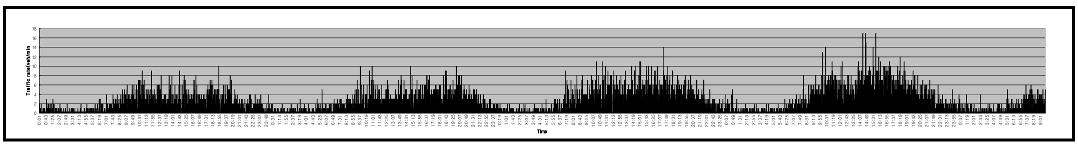
Fig. 7 shows the variation of the measurements made at 668m and 3200m locations in the 3450m-long tunnel.



a. Velocity Profiles at Two Locations



b. Velocity Differences



c. Traffic Rate

Fig. 7 Distribution of Velocity and Traffic Rate at Jansung Tunnel

Table 3 shows simple statistics and the mean value of the velocity differences is 0.05m/s. The two data sets are divided into two groups by the traffic rate, are paired and their differences are tested through t-test by the group. The results show as in Table 4 there is no difference between the two locations and its dependency on the traffic rate is not significant either.

Table 3. Simple Statistics for Jansung Tunnel

| | Near the Entrance | Near the Exit | Velocity Difference |
|---|---|---|---|
| Max | 5.60 | 5.60 | 0.40 |
| Min | -3.00 | -2.90 | -0.60 |
| Mean | 1.94 | 1.99 | -0.05 |
| Std | 1.62 | 1.60 | 0.12 |
| C.V | 0.83 | 0.80 | -2.22 |

Table 4.. Results of t-test for Jansung Tunnel

Group 1: Traffic Rate (1~5 veh/min)

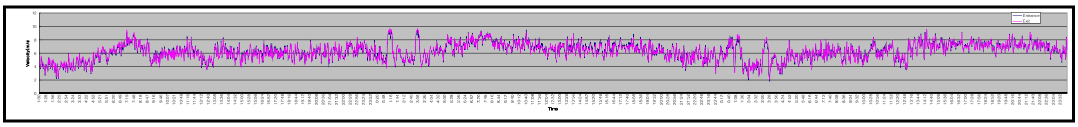
| | Entrance Measurements | Exit Measurements |
|---|---|---|
| Mean (m/s) | 2.19 | 2.26 |
| S.D. | 1.93 | 1.90 |
| Obs | 3608 | |
| d.f. | 7214 | |
| t statistics | -1.90 | |
| Result | Difference insignificant | |

Group 2: Traffic Rate (>5 veh/min)

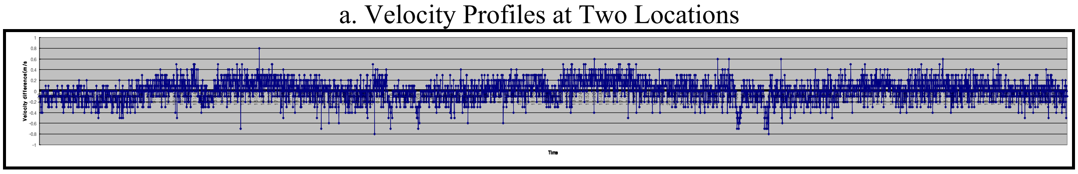
| | Entrance Measurements | Exit Measurements |
|---|---|---|
| Mean (m/s) | 2.89 | 3.00 |
| S.D. | 0.86 | 0.88 |
| Obs | 460 | |
| d.f. | 918 | |
| t statistics | -1.86 | |
| Result | Difference insignificant | |

**B. Pibanryong Tunnel**

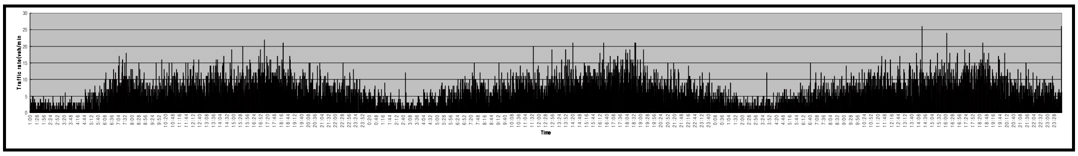
The measurements made at 100m and 1940m in 2040m-long Pibanryong tunnel are analyzed in the same way as in Jansung Tunnel. The statistical results conclude that there is no significant discrepancy between the two locations, and the traffic rate does not influence the difference considerably.



a. Velocity Profiles at Two Locations



b. Velocity Differences



c. Traffic Rate

Fig. 8 Distribution of Velocity and Traffic Rate at Pibanryong Tunnel

Table 5. Simple Statistics for Pibanryong Tunnel

| | Near the Entrance | Near the Exit | Velocity Difference |
|---|---|---|---|
| Max | 9.6 | 9.8 | 0.8 |
| Min | 1.8 | 2.1 | -0.8 |
| Mean | 6.24 | 6.24 | 0.003 |
| S.D. | 1.24 | 1.21 | 0.19 |
| C.V | 0.20 | 0.19 | 58.8 |

Table 6. Results of t-test for Pibanryong Tunnel

Group 1: Traffic Rate (1~5 veh/min)

| | Entrance Measurements | Exit Measurements |
|---|---|---|
| Mean (m/s) | 5.95 | 5.98 |
| Variance | 1.79 | 1.78 |
| Obs | 1818 | |
| d.f. | 3634 | |
| t statistics | -0.82 | |
| Result | Difference insignificant | |

Group 2: Traffic Rate (5~10 veh/min)

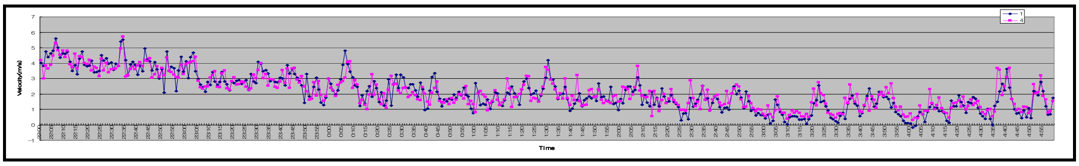
| | Entrance Measurements | Exit Measurements |
|---|---|---|
| Mean (m/s) | 6.52 | 6.49 |
| Variance | 1.10 | 1.06 |
| Obs | 1703 | |
| d.f. | 3404 | |
| t statistics | 0.92 | |
| Result | Difference insignificant | |

Group 3: Traffic Rate (>10 veh/min)

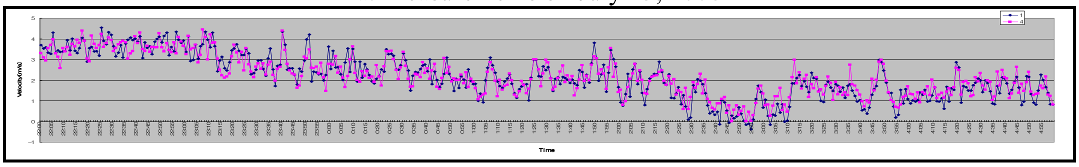
| | Entrance Measurements | Exit Measurements |
|---|---|---|
| Mean (m/s) | 6.59 | 6.53 |
| Variance | 1.01 | 0.97 |
| Obs | 568 | |
| d.f. | 1234 | |
| t statistics | 1.14 | |
| Result | Difference insignificant | |

**C. Sujungsan Tunnel**

Fig. 9 shows the velocity distributions at two locations, 400m and 1956m in 2356m-long tunnel, while two figures are from the measurements made on different days, while Fig. 10 describes the velocity profiles of the measurements from 900m and 1456m. Table 7 includes the results of t-test for the group means. It concludes that as in the previous tunnels, there can not be found any significant discrepancy between the measurements made at two locations.



a. Measurements on July 23, 2008

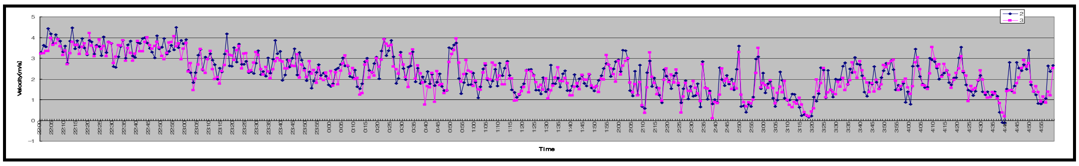


b. Measurements on July 24, 2008

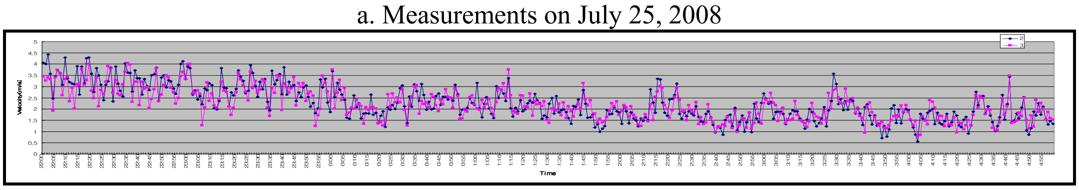
Fig. 9 Velocity Profiles at 400m and 1956m in Sujungsan Tunnel

Table 7. Results of t-test for Sujungsan Tunnel

| | Measurements at 400m | Measurements at 1956m | Measurements at 900m | Measurements at 1456m |
|---|---|---|---|---|
| | July 23, 2008 | | July 25, 2008 | |
| Mean (m/s) | 2.09 | 2.14 | 2.27 | 2.21 |
| S.D. | 1.44 | 1.17 | 0.84 | 0.75 |
| Obs | 419 | | 419 | |
| d.f. | 836 | | 836 | |
| t statistics | -0.69 | | 0.94 | |
| Result | Difference insignificant | | Difference insignificant | |
| | July 24, 2008 | | July 26, 2008 | |
| Mean (m/s) | 2.17 | 2.20 | 2.25 | 2.21 |
| S.D. | 1.14 | 0.90 | 0.61 | 0.49 |
| Obs | 419 | | 419 | |
| d.f. | 836 | | 836 | |
| t statistics | -0.48 | | 0.86 | |
| Result | Difference insignificant | | Difference insignificant | |



a. Measurements on July 25, 2008

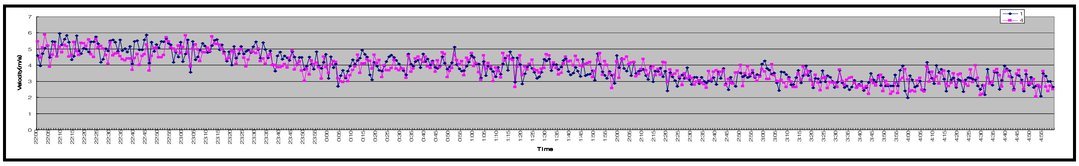


b. Measurements on July 26, 2008

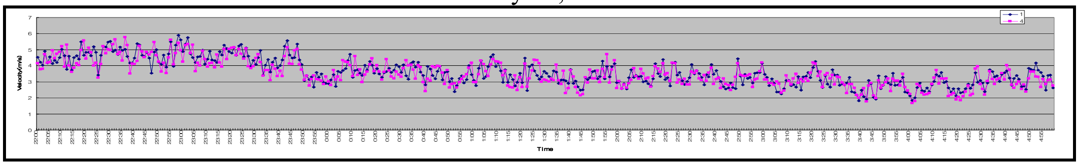
Fig. 10 Velocity Profiles at 900m and 1456m in Sujungsan Tunnel

**D. Baekyangsan Tunnel**

Fig. 11 shows the measurements at 300m and 2040m, while Fig. 12 includes the profiles at 800m and 1240m. Table 8 describes the t-test results and there is no significant difference in velocity along the tunnel as in the previous tunnels.



a. July 30, 2008

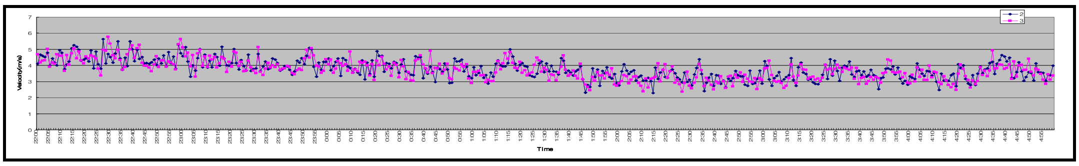


b. July 31, 2008

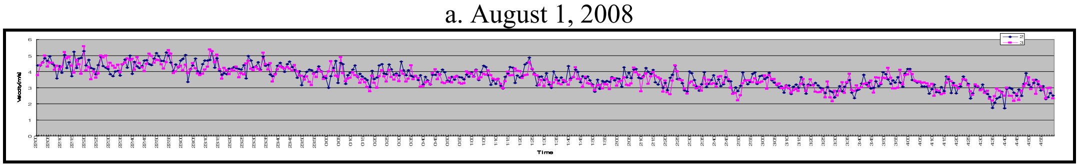
Fig. 11 Velocity Profiles at 300m and 2040m in Baekyangsan Tunnel

Table 8. Results of t-test for Sujungsan Tunnel

| | Measurements at 300m | Measurements at 2040m | Measurements at 800m | Measurements at 1240m |
|---|---|---|---|---|
| | July 30, 2008 | | August 1, 2008 | |
| Mean (m/s) | 3.86 | 3.81 | 3.77 | 3.72 |
| S.D | 0.74 | 0.65 | 0.36 | 0.39 |
| Obs | 420 | | 420 | |
| d.f. | 838 | | 838 | |
| t statistics | 0.96 | | 1.39 | |
| Result | Difference insignificant | | Difference insignificant | |
| | July 31, 2008 | | August 2, 2008 | |
| Mean (m/s) | 3.59 | 3.52 | 3.67 | 3.59 |
| S.D | 0.68 | 0.67 | 0.43 | 0.41 |
| Obs | 420 | | 420 | |
| d.f. | 838 | | 838 | |
| t statistics | 1.32 | | 1.84 | |
| Result | Difference insignificant | | Difference insignificant | |



a. August 1, 2008



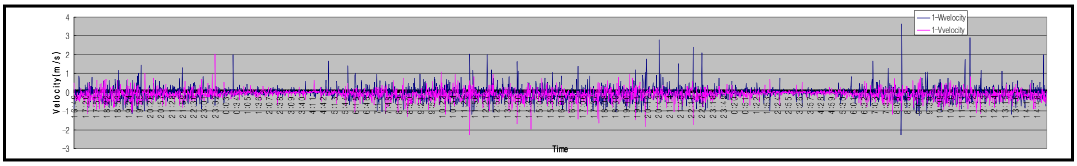
b. August 2, 2008

Fig. 12 Velocity Profiles at 800m and 1240m in Baekyangsan Tunnel

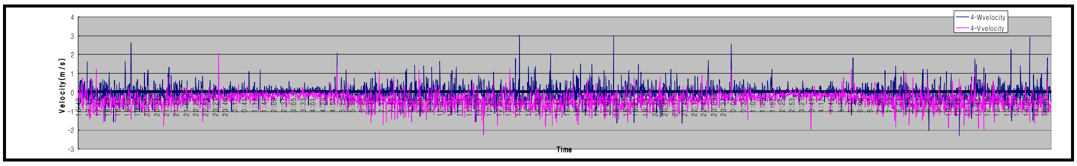
## 3.2 Variations across the cross section

### A. Vertical and horizontal variation

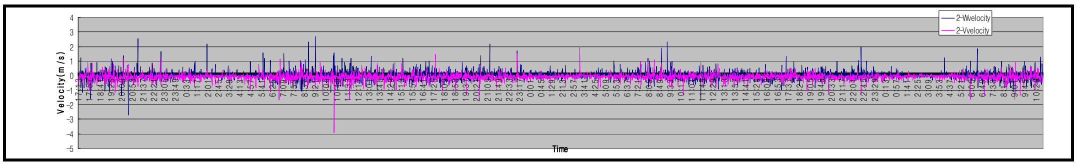
Fig. 13 depicts the vertical and horizontal velocity variation at 400, 900, 1456 and 1956m in Sujungsan Tunnel, along with Table 9 showing their simple statistics. Horizontal variation ranges from 0.08 to 0.41m/s, while the velocity in the vertical direction varies from 0.01 to 0.06m/s. Fig. 14 and Table 10 are the results from Baekyangsan Tunnel. The velocity varies horizontally from 0.02 to 0.17m/s and vertically from 0.04 to 0.08m/s. As in Sujungsan Tunnel, the horizontal velocity is found to be larger than the vertical velocity, but the coefficient of variation of vertical velocity is relatively larger. The vertical as well as horizontal variations are larger at locations closer to the exit portal with respect to the coefficient of variation.



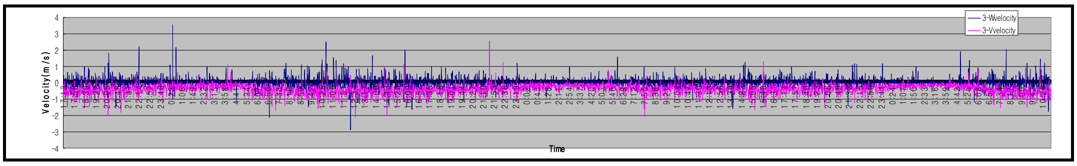

a. at 400m




b. at 1956m




c. at 900m



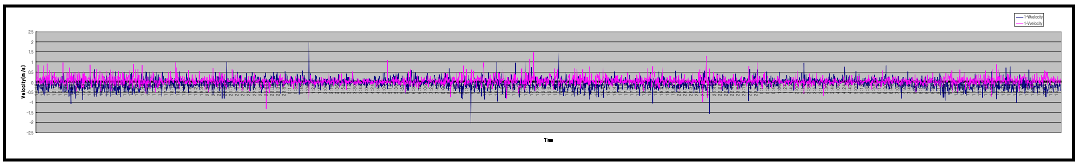

d. at 1456m

Fig. 13 Vertical and Horizontal Variation in Sujungsan Tunnel

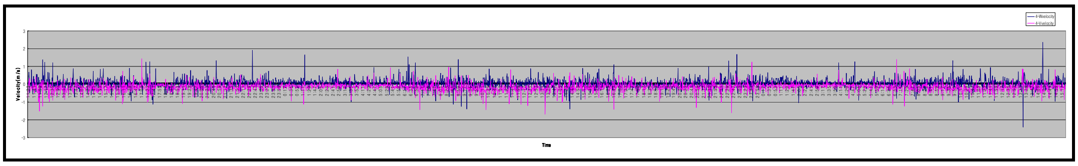
Table 9. Simple Statistics of the Vertical and Horizontal Variation in Sujungsan Tunnel

| Simple Statistics | at 400m | | at 1956m | |
|---|---|---|---|---|
| | Horizontal(m/s) | Vertical(m/s) | Horizontal(m/s) | Vertical(m/s) |
| Mean | -0.11 | -0.06 | -0.41 | -0.04 |
| S.D. | 0.28 | 0.36 | 0.39 | 0.44 |
| | at 900m | | at 1456m | |
| Mean | -0.08 | 0.01 | -0.38 | 0.01 |
| S.D. | 0.25 | 0.30 | 0.30 | 0.32 |

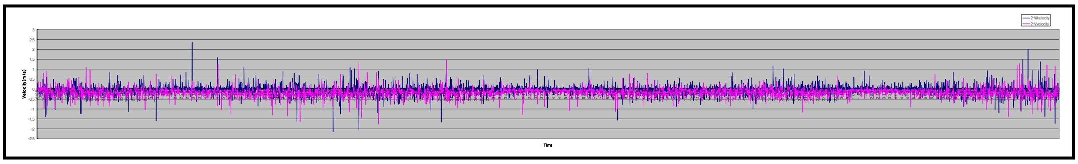
Fig. 14 and Table 10 are the cases from Baekyangsan Tunnel; measurements were made at 300, 800, 1240 and 2040m.



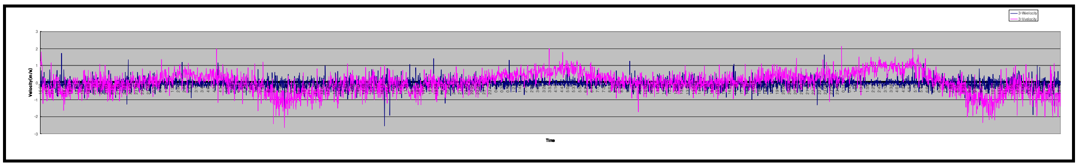
a. at 300m



b. at 2040m



c. at 800m



d. at 1240m

Fig. 14 Vertical and Horizontal Variation in Baekyangsan Tunnel

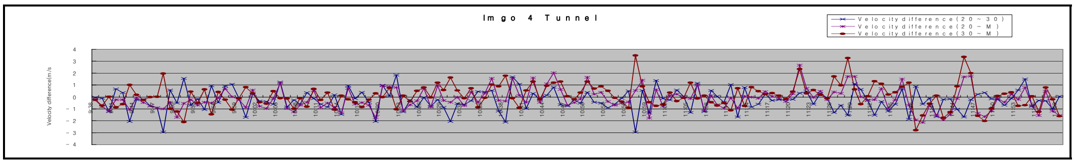
Table 10. Simple Statistics of the Vertical and Horizontal Variation in Baekyangsan Tunnel

| Simple Statistics | at 300m | | at 2040m | |
|---|---|---|---|---|
| | Horizontal(m/s) | Vertical(m/s) | Horizontal(m/s) | Vertical(m/s) |
| Mean | 0.06 | -0.07 | -0.16 | 0.04 |
| S.D. | 0.19 | 0.24 | 0.28 | 0.28 |
| | at 800m | | at 1240m | |
| Mean | -0.17 | -0.07 | 0.02 | -0.08 |
| S.D. | 0.23 | 0.26 | 0.60 | 0.27 |

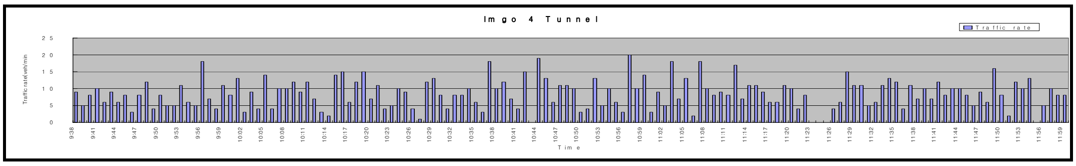
**B. Near-wall variation at Imgo 4 Tunnel**

As mentioned in the introduction, the cross-sectional variation of the velocity is a very important subject since some types of the velocity monitor assume that the cross-sectional distribution is close to uniform. To test the cross-sectional variation, the monitors were installed at the same location as the ultrasonic monitor the tunnel has. The monitors at tunnels measure the velocity profiles over the diagonal on the cross section and is supposed to record the mean velocity. The experiments were carried out at Imgo 4 Tunnel by installing 3-D monitors at 20cm and 50cm from the wall.

Fig. 15~17 show the velocity differences among the three groups of measurements: cross-sectionally scanned, 20cm and 50cm measurements along with the traffic rates.

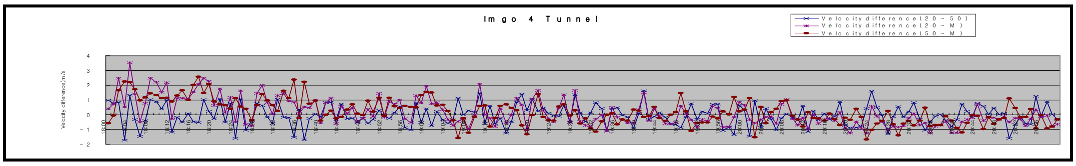



a. Velocity difference (09:00~12:00)

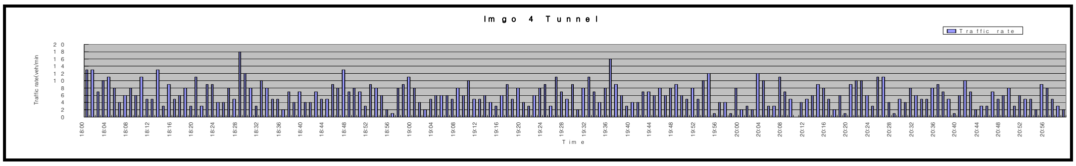



b. Traffic rate (09:00~12:00)

Fig. 15 Measurements at Imgo 4 Tunnel (1)

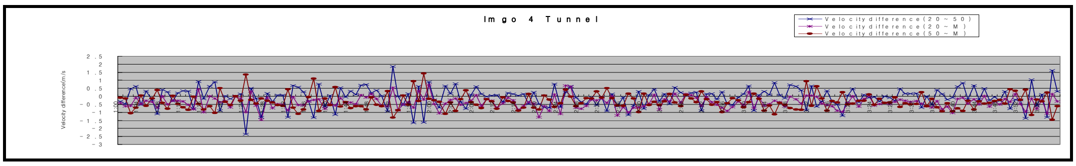



a. Velocity difference (18:00~21:00)

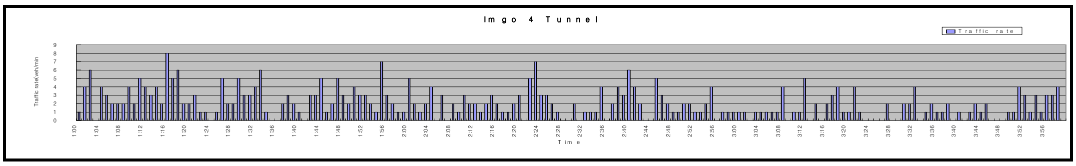



b. Traffic rate (18:00~21:00)

Fig. 16 Measurements at Imgo 4 Tunnel (2)




a. Velocity difference (01:00~04:00)




b. Traffic rate (01:00~04:00)

Fig. 17 Measurements at Imgo 4 Tunnel (3)

Table 11 summaries the simple statistics of the three sets of measurement. All the recorded data were divided into three groups with different traffic rates. The difference between the measurements from 20cm and 50cm off the wall is in the range of 0.05~0.27m/s, while compared with the data from the ultrasonic monitor scanning the whole cross section, the data recorded at 20cm shows the difference ranging between 0.18 and 0.39m/s and differences with those from 50cm ranges between 0.09 and 0.33m/s. These differences are not founded to be significant considering the standard deviations which ranges from 0.47~0.99m/s. In general, measurements closer to the wall show smaller difference from the cross-sectionally scanned data.

Table 11. Simple Statistics at Imgo 4 Tunnel

| | Measurement Locations | | | Velocity Differences | | | Traffic Rate | | |
|---|---|---|---|---|---|---|---|---|---|
| | 20cm | 50cm | cross | between | between | between | Large | Small | Total |
| 09:00~12:00 | | | | | | | | | |
| Mean | 3.96 | 4.2 | 4.14 | -0.27 | -0.18 | 0.09 | 0.64 | 7.81 | 8.45 |
| S.D. | 0.76 | 0.85 | 0.78 | 0.88 | 0.90 | 0.99 | 1.07 | 4.06 | 4.27 |
| 18:00~21:00 | | | | | | | | | |
| Mean | 3.40 | 3.43 | 3.23 | -0.03 | 0.16 | 0.19 | 0.27 | 6.10 | 6.37 |
| S.D. | 0.61 | 0.62 | 0.76 | 0.72 | 0.916 | 0.84 | 0.51 | 3.01 | 3.10 |
| 01:00~04:00 | | | | | | | | | |
| Mean | 2.777 | 2.83 | 3.16 | -0.05 | -0.39 | -0.33 | 0.20 | 1.86 | 2.06 |
| S.D. | 0.48 | 0.56 | 0.35 | 0.60 | 0.37 | 0.47 | 0.48 | 1.61 | 1.69 |

## 4. Conclusions

This paper aims at studying the three dimensional variation of the airflow velocity in road tunnels. The results are summarized as follows:

(1) Due to the jet stream, cross-sectional velocity distribution near the wall varies with the distance and becomes uniform at approximately 145 meters downstream, while axial velocity reaches a constant value at about 200 meters from fans.

(2) Regardless of height above the road surface, the longitudinal air velocity varies insignificantly in the range of 0.4 to 2m from the wall. In the tunnels open to traffic, outside this range the velocity is almost constant due to the moving vehicles

(3) Longitudinal velocity difference is not significant along the tunnel and its dependency on the traffic rate is not significant.

(4) Horizontal velocity is found to be larger than vertical velocity, while the coefficient of variation of vertical velocity is relatively larger. The vertical as well as horizontal variations are larger at locations closer to the exit portal.

(5) Compared with the velocities from the ultrasonic monitor scanning the whole cross section, the measurements from 20cm and 50cm off the wall do not show statistically significant discrepancy with the differences ranging from 0.05 to 0.27m/s.

## Acknowledgments

The authors gratefully acknowledge CUFER (Center for underground fire and environment research), KICTTEP (Korea Institute for Construction and Transportation Technology Evaluation and Planning) and Korea Expressway Corporation for providing financial support and necessary resources that have contributed to the research results reported within this paper.

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