An experimental study on the shock loss at the junction of double-deck road-tunnel network

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ABSTRACT

The number of cases operating urban double-deck tunnels has been increasing due to the advantages of the operation of double-deck tunnels over the world. To alleviate severe traffic congestion, a project of a double-deck road-tunnel network was planned in Seoul, Korea. The main characteristics of a planned double-deck tunnel in Korea is the presence of a network, which means the existence of various combining and dividing flows at the junction. This characteristic requires the design factors for shock loss on the ventilation system. This study examined the shock loss of combining and dividing flows and suggests a new factor for the design of a ventilation system. An experimental study was conducted with a 1:23 scaled model by referring to the design cross-section of the planned double-deck tunnel and the aspect ratio of the scaled model was 3:1. This high aspect ratio is because the height of the double-deck tunnel for a small car is lower than that of a classical tunnel. The results from this experimental study were compared with the data obtained from theoretical equations. As a result, the trend of values from this experiment showed reasonable differences: overall approximately 0.13 ~ 0.49 higher values of shock loss coefficient. The experimental result was up to three times higher than the values obtained from theoretical equations. The result showed that the shock loss coefficient from the 1:1 aspect ratio of ducts or pipes cannot be applied to that from the 3:1 aspect ratio of double-deck tunnel. Overall, the results of this study can be used to determine the shock loss on combining and separating flows at the junction in the ventilation design.

1. INTRODUCTION

Double-deck tunnels, such as the A86 tunnel in France, M30 tunnel in Spain, and Smart tunnel in Malaysia, have successfully alleviated urban traffic congestion for the past several years. South Korea recently launched a new project on a double-deck
tunnel of its own in Seoul, called U-Smartway. The U-Smartway project was planned to be designed for small cars and is to be constructed in a network shape, with three tunnels in the longitudinal direction and the other three tunnels in the transverse direction across the city of Seoul, as shown in Fig. 1.

![Deep road tunnel planning](image1.png)  ![A bird's eyes view JCT](image2.png)

**Fig. 1 Concepts of U-Smartway (Kim 2011)**

The construction and operation of such urban structures are accompanied by the issues of environmental safety and human health, particularly the air quality inside the tunnel. Because the long-term exposure to air polluted from vehicle emissions can have adverse health effects, such as respiratory and cardiovascular diseases (Bjornback 2000), the ventilation system must be required to provide the health protection on the normal operation of a road tunnel. In classical tunnels, the design of a ventilation system can be based on the types of longitudinal or transverse airflow, which is flowed through a tunnel tube or duct system. However, additional design factors should be considered in the selection and design of ventilation system because of the characteristics of the double-deck road-tunnel network system. The report from PIARC (2016) pointed out that the “major design parameter” depends on the presence or absence of tunnel connections, where airflow control is required for air quality. The structure of a road-tunnel network indicates the existence of underground interchanges between each double-deck tunnel, and the aerodynamic system at the junction represents the various combining and dividing flows. The circumstances of airflow in a tunnel network can lead to pressure losses due to a shock at the junction. For the ventilation system design of a road tunnel, an estimation of the amount of the pressure losses is important for calculating the fan capacity required to provide fresh air and dilute vehicle emissions and pollutants.

Many experimental studies examined the shock loss with pipe-network structures, mainly T-shaped and Y-shaped pipes. Miller (1971, 1990) and ESDU (1973a, b) offered several charts from their experimental results of the shock loss coefficient with various angles and area ratios of the steady flow combination and division at pipe junctions. In those charts, the flow ratio was the main parameter to determine the shock loss coefficient. Gardel (1957a, b) conducted shock loss-coefficient experiments for the effects of the angle on various T-shaped junctions and
suggested the empirical equations that included the factor of angles between the main pipe and branch pipe. Wood (1993) examined the modeling of network flow analysis using these empirical equations that explained the results of the T-junction experiments from Idlechik (1986) and Miller (1971, 1990). Serre (1994) suggested their equation to calculate the shock loss coefficient of the experimental results within a 15% accuracy for the T-junction with an area ratio of the branch to the main pipe, ranging from 0.02 to 0.21. Michalos (2011) compared the equation suggested by Gardel (1957a, b) with Miller’s chart and reported that there was no agreement on the shock loss coefficient for combining flow at a main pipe and for dividing flow from a main pipe to a branch where the area ratio is lower than 0.5. Consequently, Michalos (2011) proposed another equation that approximates in the entire range of Miller’s chart. Hager (1984) attempted a theoretical approach to describe the influence of the flow angle at the junction from previous experimental studies. Bassett (2001) developed the theoretical study of Hager (1984), and suggested equations for the various angles and area ratios at the combining and dividing flows; the equations showed a good agreement with Miller’s experiment.

As previous studies of shock loss were conducted mainly for ducts or pipes, their shape was selected as a circular or not high aspect-ratio rectangular. On the other hand, the shock loss-coefficient data from previous studies cannot be used due to the large dimension and high aspect ratio, which reaches 3:1 because the double-deck road-tunnel project is to be designed for small cars. Jade (2008) reviewed the factors governing shock loss that can be a function of the velocity ratio, deflection ratio, area ratio, and Reynolds number. In this study, experimental test was conducted with a scaled model that refers to the actual cross-section design of the planned U-Smartway double-deck tunnel to calculate the shock loss coefficient that can occurs at the combining and dividing flows in a real circumstance.

2. Shock loss

Shock loss means the pressure loss that occurs due to an abrupt discontinuity in the flow field, such as a change in section area, flow direction or structures, where the airway can be interrupted.

\[ P_x = K \cdot P_r \]  \hspace{1cm} (1)

where \( P_x \) is the pressure loss due to shock [Pa]; \( P_r \) is the velocity pressure drop[Pa]; and \( K \) is the shock loss coefficient. If the shock loss coefficient is known at a certain flow field, the amount of shock loss that occurs can be estimated. From Eq. (1), the shock loss coefficient can be converted to Eq. (2) and the coefficient can be measured.

\[ K_i = \frac{P_{T,up} - P_{T,down}}{P_{T,com}} = \frac{(P_{S,up} + \frac{1}{2} \rho v_{up}^2) - (P_{S,down} + \frac{1}{2} \rho v_{down}^2)}{\frac{1}{2} \rho v_{com}^2} \]  \hspace{1cm} (2)
where $P_T$ is total pressure [Pa]; $P_S$ is the static pressure [Pa]; $v$ is the air velocity [m/s]; $\rho$ is the air density; and the indices of up, down, and com refer to the upstream, downstream and common pipe, respectively. On the other hand, these formulations of the shock loss coefficient cannot represent the governing parameters of the mass flow ratio, deflection angle, and area ratio, which were considered in previous studies, as well as the aspect ratio on which this study is focused.

With two types of flow directions, such as three separating flows and three joining flows, the shock loss coefficient can be categorized into a total of 6 flow types, depicted in Fig. 2. While Fig. 2 shows only three legs, the structure can be varied further when the number of legs increases. As this study was only concerned with the flow field of the joining and separating flows at the junction of a uni-direction road tunnel, only flow types 3 and 4 in Fig. 2 are considered. Air flow in a road tunnel is caused mainly by traffic movement that leads to a “piston effect” or an installed fan that increase the pressure head. As it is supposed that traffic flows from the leg 1 to the leg 3 in Fig. 2, it is difficult to consider the other flow types due to the aerodynamic system that the airway direction follows the traffic direction in general, and our experimental study was performed to determine only the shock loss coefficient $K_3$, $K_4$, $K_{11}$, and $K_{12}$, by controlling the flow ratio based on Eq. (2).

In addition, the difference in the shock loss coefficient by the aspect ratios was studied by comparing the experimental results with theoretical equations suggested by Basset (2001). Basset (2011) proposed the formulation from the momentum equation to calculate the 6 types of coefficient in Fig. 2, considering the influence of the area ratio and angle, assuming a constant aspect ratio, and neglecting the influence of the cross-section shape, such as the circular or rectangular section. Because the double-deck tunnel that was concerned in this study was for light vehicles with the shape of a rectangle and an aspect ratio of 3:1, the difference in the result of the aspect-ratio...
The influence was analyzed by comparing with the theoretical equation. The equations for $K_5$, $K_6$, $K_{11}$, and $K_{12}$ are expressed in Eqs. (3) – (6), respectively.

$$K_5 = q^2 - \frac{3}{2} q + \frac{1}{2}$$  \hspace{1cm} (3)

$$K_6 = q^2 \psi^2 + 1 - 2q\psi \cos\left(\frac{3}{4}\theta\right)$$  \hspace{1cm} (4)

$$K_{11} = \frac{2\psi}{\psi + \frac{1}{2}\cos \theta} \left[1 - q^2 - (1 - q)^2 \psi \cos \theta\right] + q^2 - 1$$  \hspace{1cm} (5)

$$K_{12} = \frac{2\psi}{\psi + \frac{1}{2}\cos \theta} \left[1 - (1 - q)^2 - q^2 \psi \cos \theta\right] + q^2 \psi^2 - 1$$  \hspace{1cm} (6)

where $q$ is the flow ratio, $\theta$ is the deflection angle, and $\psi$ is the area ratio, which represents the ratio of the main-branch area to the joining- and separating-branch area, $\frac{\text{Area}_{\text{Leg 1}}}{\text{Area}_{\text{Leg 3}}}$. The area ratio $\psi$ of 1 and 1.8 was used in the case of 2 lanes and 1 lane on the combining and dividing road tunnel (refers to Leg 3), respectively. As shown in the equations above, the shock loss coefficient $K$, is dependent only on three factors, the flow ratio, area ratio, and deflection angle. Because the equation suggested by Bassett (2001) is for the constant aspect ratio of pipe section, the major difference in the experimental result of the tunnel can be due to the aspect ratio, which accounts for 3:1.

3. Experimental Content

3.1 Experiment model

The experiment model was scaled by 1/23 by referring to the expected cross section design of the U-Smartway tunnel. The cross-section design planned in the double-deck tunnel is for a light vehicle with a 9.25 m width for 2 lanes and a 3 m height, and the combining and dividing tunnel was planned as 1 lane. Accordingly, the experiment model was made as acrylic plates with a 0.4 m width, 0.13 m height and 10 m length, and the width and height of the combining and dividing tunnel model was 0.22 m and 0.13 m, respectively, supposed as 1 lane. The angle of the junction between the main tunnel and the combining and dividing tunnel was 30° and 45°. Fig. 3 shows the experiment model, and Fig. 4 presents the total pressure and velocity pressure measured by 5 Pitot tubes located along the measurement points at the same interval. The dampers installed in each exit and entry, as shown in Fig.3(c), was to control the flow rate at each leg. The air velocities that were required to calculate the shock loss coefficient were calculated from the velocity pressure measured by the pitot tubes and standard air density of 1.2 kg/m$^3$ was used.

3.2 Similarity law

The similarity law should be considered because the purpose of this study was to suggest the design factor that can be applied to a real tunnel. Therefore, the
experimental result can be used for a real tunnel in the case that the similarity law is satisfied in terms of the fluid flow and pressure. Geometric similarity was considered for the model tunnel and real tunnel. The scaled model should satisfy Eq. (6), where the geometric scaling factor is \( \lambda \).

\[
\lambda L_S = L_R \quad (6)
\]

Moreover, an attempt was made to identify the Reynolds number between model tunnel and full-scale tunnel by applying the Reynolds similarity law. The Reynolds similarity law is generally applied in the fluid flow, such as airway, particularly in the flow field where viscous forces are dominant. The similarity law for the Reynolds number can be represented as Eq. (7).

\[
\left( \frac{\rho V D}{\mu} \right)_S = \left( \frac{\rho V D}{\mu} \right)_R \quad (7)
\]

where the index of S denotes the scaled model and that of R represents the real scale. Tien (1988) reported that a Reynolds number above 50,000 has no considerable influence on the pressure coefficient. Ito (2005) and Jade (2008) carried out T-shaped model experiments at Reynolds numbers above 30,000 and 10,000, respectively. The minimum air velocity in the model tunnel was determined to be 1 m/s and Reynolds number was maintained above 15,000. Axial fans capable of achieving an air velocity up to 10 m/s were installed to form various flow rates. The eddies generated by these fans were minimized by the installation of a honeycomb, as shown in Fig. 3(c).

![Scaled model test](image)

**3.3 Experiment method**

As mentioned above, Fig. 4 shows the location of the fans to conduct the experiment of flow types 3 and 6 in Fig. 2. To measure the shock loss coefficient at the dividing flow of flow type 3, a fan was installed in leg 1 and dampers were attached in
legs 2 and 3 to control the air flow ratio. A fan and honeycomb were attached to legs 2 and 3 for the combining flow of flow type 6 at the junction. The arithmetic mean was calculated from the data measured 2 times at each location. In addition, the negative-pressure data were processed to be zero at a certain turbulence zone according to the recommendation of ASHRAE (2009).

4. Result

4.1 Dividing flow

Figs. 5 and 6 present the experiment results of dividing flow with a comparison with the plot of Eqs. (3) and (4). Considering the pattern of the theoretical equations that are expressed as quadratic functions of the flow ratio, Figs. 5 and 6 also show the quadratic regression curve from the shock loss coefficients measured from the experiment. The X-axis and Y-axis indicates the air flow ratio between legs and shock loss coefficient in each figure and the indices of the air flow ratio represents the number of legs described in Fig. 4. In the dividing flow at the junction, Fig. 5 shows the shock loss coefficient, \( K_5 \), along the main road tunnel. The experimental results were fitted to the regression curve by 30° and 45° of the division angle. Because \( K_5 \) is dependent only on the flow ratio, as seen in Eq. (3), the angle and area ratio have no influence on the shock loss coefficient, theoretically. On the other hand, there was a slight difference in the regression curve when the lane width of leg 3 was narrowed to 1 lane, as shown in Fig. 5(b). Nevertheless, the overall range of experimental values by the flow rate
showed a similar level of results. Consequently, the shock loss coefficient, $K_5$, was approximately three times higher than that obtained by the theoretical equation.

Fig. 5 Comparison of the shock loss coefficient, $K_5$, between the experiment result and Eq. (3)
Fig. 6 presents the results and a comparison of the shock loss coefficient $K_6$ on dividing flows at the junction. According to Eq. (4), $K_6$ is influenced by the angle, flow ratio, and area ratio. The shock loss coefficient increased with increasing angle, and as the area was decreased to 1 lane, there was a lower range of the shock loss coefficient than at 2 lanes at a lower flow ratio, whereas there was a wider distribution of the shock loss coefficients than at 2 lanes at a higher flow ratio. This trend can be identified in Eq. (4) and the shock loss coefficient increases significantly with increasing aspect ratio. On the other hand, the regression curve showed a different trend in the case of 2 lanes, as shown in Fig. 6(a). This was attributed to the circumstance that negative values were measured in three measurement points from a total of five measurement locations due to considerably large turbulence field at the dividing junction. Therefore, the turbulence field increased because the aspect ratio of the section is larger than 1 lane. Accordingly, the result of these graphs can be considered as the characteristic result due to the higher aspect ratio. On the other hand, the regression curve was similar to the theoretical equation because the aspect ratio decreased to 1:1.8 in the case of a dividing flow of 1 lane. These results highlight the necessity of further studies on the shock loss dependent on a high aspect ratio.
4.2 Combining flow

In the case of combining flow, the experiment was conducted in terms of the angle and area ratio of the combining road, as shown in Fig. 4(b). The theoretical equations of Eqs. (5) and (6) were applied to the combining flow. Because the two equations showed no sufficient agreement with Miller’s chart (1971), (Bassett 2001) suggested a correction method. The correction factor of \( \frac{3}{4} \theta \) was applied to the equations, resulting in good agreement with the experimental values. This study used Eqs. (5) and (6) with the correction factor. Fig. 7 shows the experimental results of combining the flow at the main road. As the angle increased, the shock loss coefficient, \( K_{11} \), increased and the experimental result was higher than that predicted by the theoretical equations. In the theoretical equation, the shock loss coefficient decreased significantly with decreasing width of the road lane, whereas there was no considerable difference in the experimental result.

Fig. 8 presents the result of the shock loss coefficient, \( K_{12} \), at the same combining flow. The shock loss coefficient was measured to be higher when the angle of the combining flow increased, as shown in the theoretical equation. In the case of \( K_{12} \), the experimental result was higher than that predicted by the theoretical equation with only a small difference.
The shock loss coefficient can represent the pressure loss at both the dividing and combining flows. On the other hand, the results of combining flows showed the negative coefficient range on both figs. 7 and 8 at a low flow ratio. The pressure change due to the shock loss at this range is believed to lead to an increase in the pressure head. According to Schmandt (2015), this range occurs at only the combining flow because the combining flow from legs 2 or 3 receives more energy transferred by viscous stresses that exceed the dissipation (see Schmandt (2015) for details). In figs 7 and 8, the negative coefficients of the experimental result ranged from a lower flow ratio than that of the theoretical result. This suggests that a large aspect ratio causes combining flows to accept less energy. The quantification of the aspect-ratio’s influence on the coefficient will be a subject of future work. In addition, although (Schmandt 2015) suggested the shock loss coefficient be called the “head change coefficient”, this study used the term, shock loss coefficient.
Fig. 7 Comparison of the shock loss coefficient $K_{11}$ between the experimental result and Eq. (5)
5. Conclusion

An experimental study of the shock loss coefficient that can occur at combining and dividing flows was conducted using a scaled model to design the ventilation system of a double-deck road-tunnel network for a small car. The experiment was carried out on a 1/23 scale by a 3:1 aspect-ratio of the rectangle section and a combining and dividing angle of 30 and 45°, respectively. While the main tunnel runs 2 lanes, the combining and dividing tunnel was supposed to be for 1 lane. A total of four types of shock loss coefficients were measured and the measured values were compared with the theoretical equations suggested by Bassett (2001), which is the most recent study and not based on a high aspect ratio. These result of this study can be summarized as follows:

1) In the case of shock loss coefficient, $K_5$, at a dividing flow, the result increased with increasing aspect ratio compared to the theoretical equation. The flow ratio of 0.3, 0.5, 0.7, and 0.9, where the experimental values were well-represented, were measured to be approximately 0.3 higher than the theoretical values, and the pattern of the theoretical equations, Eq. (3), showed that the angle or area ratio had no influence.

2) In the case of $K_6$, although the regression curve ($R = 0.99$) was well reflected in the dividing flow, there was a difference in the pattern of the theoretical equation.

Fig. 8 Comparison of the shock loss coefficient $K_{12}$ between the experiment result and Eq. (6)
This was attributed to the generation of a turbulent zone, which was highest in the dividing flow at the two-lane junction. On the other hand, there was a regression curve that reflected the pattern of the theoretical equation because the turbulent zone became smaller in the case of dividing flow at a 1-lane junction, where the area decreases. As a result of the calculation of the error at a flow ratio of 0.3, 0.5, 0.7, and 0.9, the experimental result was approximately 0.45 and 0.28 higher, which were the most significant differences due to the characteristics of the aspect ratio, than the theoretical equation at the 2-lane junction and 1-lane junction, respectively.

3) In the case of $K_{11}$ on combining flow at the 2-lane junction, the result was approximately 0.21 higher than that of the theoretical equation. On the other hand, in the case of the 1-lane junction, there was a considerable difference between the experimental result and the theoretical value. In the case of the theoretical equation, the shock loss coefficient at a low flow rate was exceptionally low as the cross-sectional area decreased, but this trend was not shown in the experiment values.

4) $K_{12}$ at the combining flow was only approximately 0.2 higher for a two-lane junction and 0.25 higher for a one-lane junction, and it showed the regression curve closest to the pattern of the theoretical equation.

5) As a result of the four types of shock loss by two angles and two-roadway areas, the overall experimental values were higher than the theoretical equations. Although the pattern of the theoretical equations was reflected sufficiently, the most significant differences were obtained in the result of $K_6$ on the dividing flow at the 2-lane junction and that of $K_{11}$ on combining flow at the 1-lane junction compared to the theoretical equations.

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REFERENCES


