# Capacity and Bottleneck Analysis of Tunnel-Group Freeway

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**Abstract:** A 30km section of freeway No. 5 in Taiwan to the north of Pinglin toll plaza was a freeway with tunnel group. The operating characteristics of the tunnel-group freeway were little known in the world. Especially it contained Sheasan tunnel with the length of 12.9km. This study conducted VD data analysis and found that the section from the northbound Shiding tunnel entrance to the 4km mark, the section from the midpoint of northbound Sheasan tunnel to the upstream including Toucheng interchange (about 10km) and the section from southbound Shiding tunnel to Pernsan tunnel (about 10km) were easily to be congested. The occurrence time and locations of congestion could be explained reasonably by the relationship of flow-rate and speed, and capacity of freeway. The traffic authority could reference these traffic characteristics to make more specific traffic control strategies, and to improve the operating efficiency and safety of this tunnel-group freeway.

***Keywords*****:** Long tunnel, Relationship of flow rate and speed, Capacity, Speed limit

## 1. INTROUUCTION

The freeway No. 5 in Taiwan contained Sheasan tunnel with the length of 12.9km. This is the sixth longest highway tunnel in the world (Taiwan Area National Freeway Bureau, 2008). This freeway has two one-way tunnels for traffic in opposite directions, and each tunnel has two lanes (lane width is 3.5m, 0.3m shoulder on both sides and 1m sidewalk). The freeway passes through Sheasan mountain area, with a height of 3,886m. The tunnel group section to the north of Toucheng toll plaza (30km mark), as shown in Figure 1, includes Sheasan tunnel (12.9km), Pernsan tunnel (3.8km), Shiding tunnel (2.7km) and other shorter tunnels.

The highway tunnel is a potential traffic flow bottleneck, but the tunnel capacity varies widely. The capacity of highway section is the average maximum traffic flow rate maintained for at least 15 minutes constantly (Transportation Research Board, 2000). Koshi *et al*. (1992) indicated that the capacity of highway tunnels in Japan was 1,100~1,350 vehicle/h/lane (vphpl). Livinson *et al*. (1985) found that the capacity of the Callahan tunnel in New York was approximately 1,600 vphpl. Chin and May (1991) found that the capacity of a section of the California highway No. 24, at the 60m mark of the exit of the 900m long Caldecott tunnel, was 2,000 vphpl. The operating characteristics of long highway tunnels were little understood at present (Lin and Su, 2009; Chang *et al*., 2010).

Lemke (2000) indicated that the highway tunnel is safer than open highway sections. However, the accidents occurred in Mont Blanc, Tauern and Gotthard tunnels of the Alps in Europe between 1999 and 2001 (IAM Mororing Trust, 2008) attracted concerns for the traffic safety of long tunnels. Therefore, the Taiwan Area National Freeway Bureau (TANFB) set restrictions on the vehicle type and running speed on highway No. 5, and allowed only small

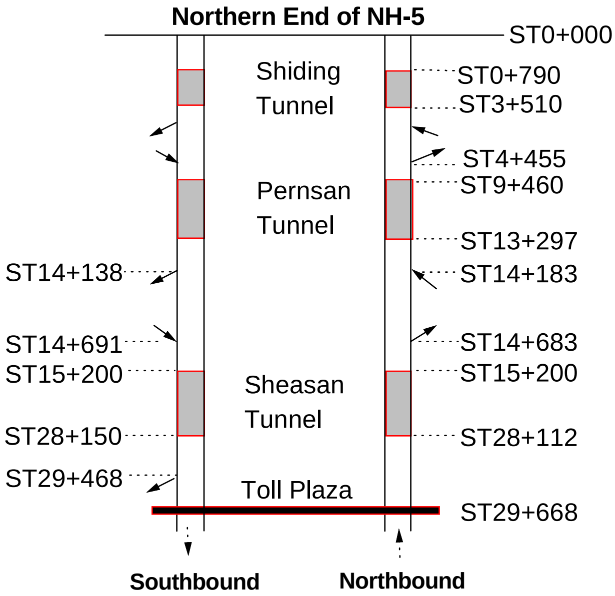


Figure 1. Schematic of the freeway Npo. 5 between station ST0+000 and ST29+668

vehicles (passenger car less than 9 seats or other vehicle less than 3,000 kg weight) to pass through Sheasan tunnel before October 2007, and speed limit at 70 km/h. After October 2007, TANFB still limited the speed limit in Sheasan tunnel at 70 km/h, while the speed limit of other sections of freeway No. 5 was increased to 80km/hr. Since November 2007, Sheasan tunnel has been opened to buses. Since March 16, 2008, the speed limit in Sheasan tunnel had been increased to 80 km/h. After reviewing the geometrical conditions of freeway No.5, the speed limit was increased to 90km/h on November 1, 2010. The speed limit in the northbound section of Sheasan tunnel to Pinglin interchange was 80 km/h, and the speed limit in other sections was 90 km/h. However, this tunnel group freeway had obvious directionality traffic flow during holidays, especially the northbound traffic jam on the end of holidays. Therefore, how to upgrade the freeway operating quality is an interesting issue for freeway authority.

Sheasan tunnel was settled with many traffic management equipments, including loop detectors at intervals of 350 m on each lane and CCTV systems at intervals of 170 m (Institute of Transportation, 2012). The loop detector can collect traffic flow data, such as flow rate, vehicle type, speed and occupancy, which were stored in 5-minute data format. These detectors had accumulated considerable traffic data, from which the traffic flow characteristics of this tunnel group freeway could be known. This study aims to use the data of these detectors to discuss the capacity and bottleneck of this tunnel group freeway, and to provide some information for TANFB to determine the traffic control strategies.

## 2. RELATIONSHIP OF FLOW RATE AND SPEED

### 2.1 Basic Concept of Traffic Flow Analysis

The relationships between flow rate and speed are the basic data for analyzing the highway operation. These relationships are influenced by many factors. Generally, when the average traffic flow speed is high, the related traffic flow density is low and the flow rate is also low.

The flow rate increases with the density, in the meanwhile the speed decreases. If the flow rate overs the section capacity, the traffic flow will be in an unstable state. When the flow rate from upstream exceeds the section capacity, the traffic flow will enter in a congestion condition. In this situation, the speed decreases rapidly and the passable flow rate of a section decreases. This phenomenon was shown as seven traffic flow samples from stable condition to congestion condition in Figure 2 by using freeway No. 5 VD data. As seen, the flow rate and speed had widely variance in the transition from stable condition to congestion condition. In other words, there was no definite demarcation between stable and congestion conditions. Moreover, regardless whether the traffic flow was stable, there might be large differences in the flow rate related to the same speed, and there were larger differences in the average speed related to the same flow rate. Therefore, the capacity of a section could reasonably estimate.

The capacity was referred to the maximum flow rate often passing through a fixed point (or a section) in a normal condition (e.g. speed limit, weather, vehicle types) without congestion condition. The flow rate was not the maximum value of flow rate observed in different time intervals. The capacity should be regarded as the expected value of maximum flow rate (i.e. mean value) before the traffic flow enters in congestion condition from stable condition. In addition, highway capacity analysis was generally using the traffic flow condition in 15-minute peak or longer time interval. Therefore, the capacity was the flow rate that kept for at least 15 minutes.

As shown in Figure 3 (Type I), the data of every 15 minutes showed when the flow rate was on some certain value, the speed varied widely, and the flow rate varied very widely when the speed was on certain value. However, in the stable traffic flow condition (before speed decreases sharply), the relationship between flow rate and speed was clear. In this case, the relationship between flow rate and speed could be represented by an average relationship reasonably. In the congestion condition, the traffic flow was unstable, the relationship between flow rate and speed often changed greatly. Generally, in congestion condition, the flow rate decreased with travel speed. This characteristic was different from the phenomenon in stable condition that the flow rate increased but the speed decreased.

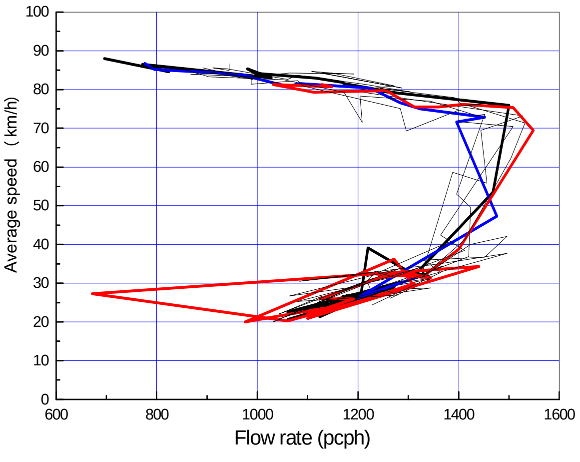


Figure 2. Relationship of flow rate and speed by traffic flow increased form stable situation to congested situation (northbound, inside lane of 27.779K)

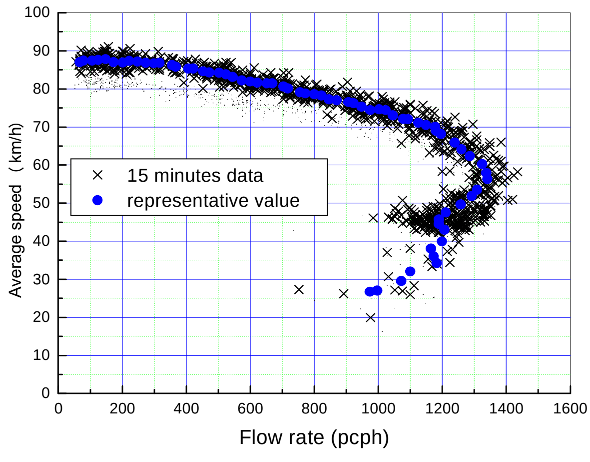


Figure 3. Relationship of flow rate and speed form every 15mins data, and the representative relationship of Type I

In order to determine the representative relationship between flow rate and speed on each location, this study integrated the detector data per five minutes into 15-minute data, and then it was divided into subregions according to the trend of relationship between flow rate and speed to estimate the overall average flow rates and speeds of individual regions. The relationship shown by these overall average flow rates and speeds was the representative relationship. Figure 4 showed a sample of representative relationship between flow rate and speed.

When the traffic flow was in congestion, the flow rate and speed data of some sites were varied in a wide range, but most data were still typical, the flow rate did not increase anymore when the speed and flow rate decreased simultaneously or the speed decreased. In this case, this study only used these concentrated data to estimate the average speed and flow rate. Therefore, the representative speed and flow rate relationship in the congestion condition only showed the approximate trend of relationship between flow rate and speed. These relationships were not applicable to planning, designing or determining control strategies.

The aforesaid objects for discussing the relationships between flow rate and speed include freeway No. 5 lengthways inside and outside lanes at the tunnel entrance, around the midpoint of tunnel and the merging section of mainline and ramp. On an average, the percentage of buses was approximately 2.5% of all-day vehicles, the buses only run in the outside lane, and the inside and outside lane flows account for almost 50% of total traffic flow respectively. Therefore, this study assumed that the buses in the outside lane account for 5% of total number of vehicles in the outside lane, and the small-veh equivalent value of buses was set as 1.5.

## 2.2 Three Basic Relationships of Flow Rate and Speed

There were three fundamental types of relationships between flow rate and speed at different locations of freeway No. 5. Type I was shown in Figure 3. Sometimes the upstream flow rate of a fixed point was limited, so it was merely a little higher than the capacity of that fixed point. The congestion increased slowly as a result, and the speed and flow rate decreased slowly.

Type II was shown as the representative relationship of speed limit 90km/hr in Figure 4. The characteristic of this type was that the speed decreased largely and rapidly when the flow rate of stable traffic flow reached a certain value, so that the traffic flow entered in considerable congestion condition rapidly. This type was generally resulted from that the flow rate from the upstream of a fixed point exceeded the capacity of the fixed point in a short period of time, and the flow rate kept exceeding the capacity for long time. This phenomenon was most usually to occur at the tunnel entrance.

Type III was shown in Figure 5. This type was special. In general stable condition and congestion condition, the speed at adjacent point was higher than 50km/hr. However, Figure 5 showed that the relationship between flow rate and speed had not yet presented simultaneous decrease of speed and flow rate when the speed was as low as 40km/hr. In this case, it was not easily to determine the capacity. The type shown in Figure 5 occurred at about downstream 300m to the northbound entrance of Shiding Tunnel.

## 2.3 Comparisons and Discussions

According to the representative flow rate-speed relationships of northbound inside lane and outside lane flowed in Sheasan tunnel, Pernsan tunnel and Shiding tunnel entrances and around the midpoints:

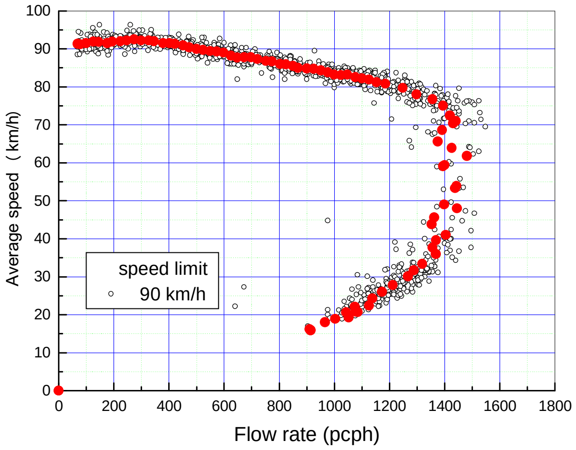


Figure 4. Relationship of flow rate and speed of Type II(inside-lane at northbound 27.779K)

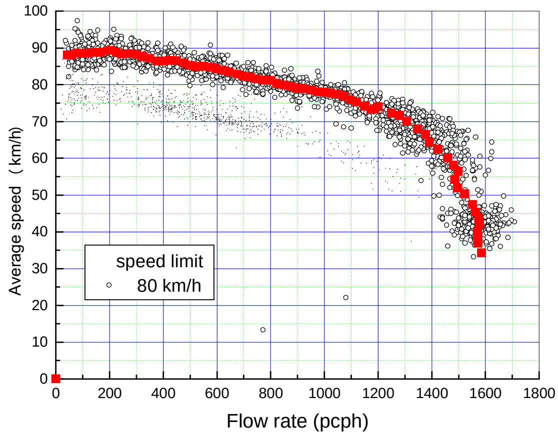


Figure 5. Relationship of flow rate and speed of Type III(inside-lane at northbound 3.198K)

1) The relationships between flow rate and speed near the midpoint (21.055K) and the exit (15.855K) of Sheasan tunnel had the most bad traffic flow characteristic. In stable traffic flow condition, the speed near the midpoint of tunnel was lower than that at other locations, and the capacity was significantly lower than that near the entrance (27.779K and 28.420K). There was an on-ramp in a short distance downstream (14.800K) to the tunnel exit, so the operating characteristic at this site was not well, too.
2) In Pernsan tunnel, the operation near the entrance (12.922K) was better than that near the midpoint (11.178K) and the exit (9.840K). This phenomenon was similar to the operation in Sheasan tunnel. In other words, the transportation capability of the two tunnels was limited to the traffic operation near the midpoint of tunnel. Pernsan tunnel entrance was next near to Pinglin interchange. Therefore, the operation at 13.348K between on-ramp and tunnel entrance was worse than that in downstream tunnel and near the tunnel exit. There was no ramp near the northbound exit of Pernsan tunnel, but there was horizontal curve with small curvature radius (700m). The capacity of the lane within 9.373K near the exit was lower than that of the upstream tunnel section. However, the outside lane at this location can keep higher speed than upstream when the flow rate was high (1,000~1,500 vphpl).
3) Shiding tunnel was only 2.7km long, its flow-rate and speed relationship showed when the flow rate was lower than 1,300 vphpl, there was little difference between the operation near the entrance (3.198K) and the exit (1.068K) in tunnel. When the flow rate was high, the speed near the entrance was lower than that near the exit. There was no significant difference between the capacity near the downstream of exit (0.706K) and that of the tunnel, but the speed at this site was usually lower than that in tunnel.
4) The northbound lanes of Sheasan tunnel and Pernsan tunnel had worse operation near the midpoints of tunnels. The worse northbound traffic operation of Shiding tunnel was near the entrance. Figure 6 and Figure 7 compared the flow-rate and speed relationship at these locations respectively. The two figures showed that there was no significant difference in the free speed of inside and outside lanes, but the capacity and related speed were quite different at different locations. In addition, the flow-rate and speed relationship in the figures clearly indicated that Sheasan tunnel had the

worst transportation capability, and Pernsan tunnel had the best transportation capability.

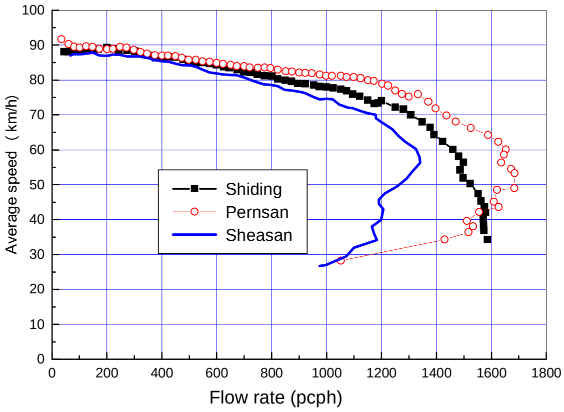


Figure 6. Comparison of flow-rate and speed relationship among three tunnels (northbound, inside lane)

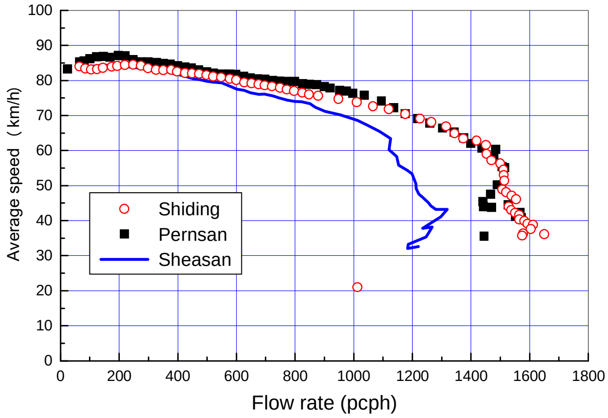


Figure 7. Comparison of flow-rate and speed relationship among three tunnels (northbound, outside lane)

According to the flow rate and speed data of southbound traffic flows in Shiding, Pernsan and Sheasan tunnels, it found:

1) The capacity of inside lane near the entrance of Shiding tunnel (1.072K) was higher than that near the exit (3.178K) and at downstream 3.500K to the exit. There was no significant difference in the operation of outside lane at the aforesaid three locations. Therefore, the southbound transportation capability of Shiding tunnel was mainly limited to the operation near the exit.
2) In stable condition, there was no significant change in the flow-rate and speed relationships of traffic flow near the entrance (9.326K) and near the exit (12.945K) of Pernsan tunnel. The inside lane and outside lane had similar operation characteristics, but when the flow rate was higher than approximately 1,300 vphpl, the tunnel entrance can keep higher speed and flow rate than upstream 9.326K. Therefore, the traffic flow might slow down in tunnel causing shock waves in the case of high flow rate.
3) The operation near the midpoint of Sheasan tunnel (21.063K) was the most worset. This phenomenon was similar to the operation of northbound section.
4) Figure 8 and Figure 9 compared the flow-rate and speed relationships at the locations with worse southbound operation of the aforesaid three tunnels. These locations included somewhere near the exit of Shiding tunnel (3.178K), near the midpoint of Pernsan tunnel (11.158K) and near the midpoint of Sheasan tunnel (21.063K). When the traffic flow was stable and the flow rates of inside and outside lanes did not exceed 1,300 and 1,200 vphpl respectively, there was slight difference in the flow-rate and speed relationships of southbound traffic flows in Shiding, Pernsan and Sheasan tunnels. When the flow rate increased, the operation of Sheasan tunnel was worse than that of other tunnels. However, this gap was much smaller than that between northbound Sheasan tunnel and other tunnels (see Figure 6).
5) The worse operation of Sheasan tunnel might be concerned with the tunnel length, other geometric design factors, lighting and wall paint. Another factor might be the specified minimum 50m spaceway in normal driving condition in Sheasan tunnel.

The influence of these factors and why the northbound capacity of Sheasan tunnel was much lower than the capacity of Shiding and Pernsan tunnels should be further discussed in the future.

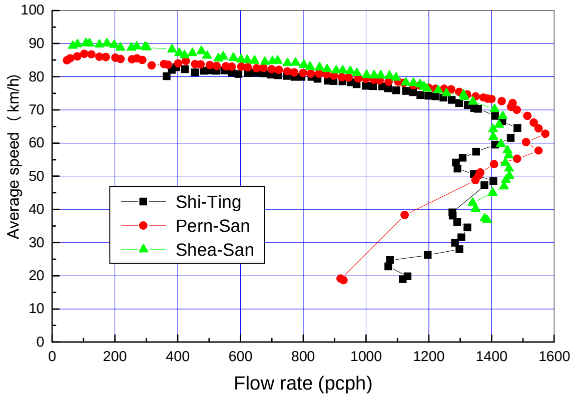


Figure 8. Comparison of flow-rate and speed relationship among three tunnels (southbound, inside lane)

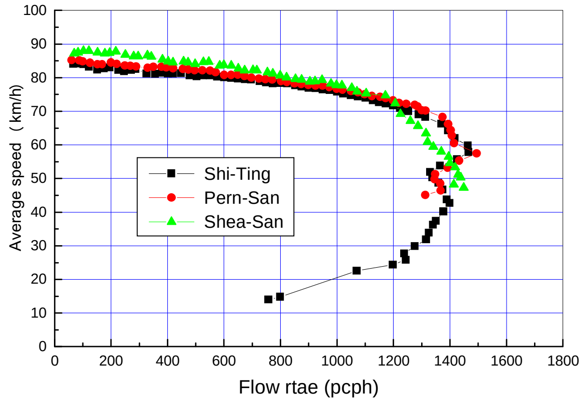


Figure 9. Comparison of flow-rate and speed relationship among three tunnels (southbound, outside lane)

The flow-rate and speed relationship of southbound and northbound near the midpoint of Sheasan tunnel was worse than upstream section. According to Figure 10, the traffic capability of northbound section of this tunnel was less than that of southbound section. The northbound capacity was lower than southbound capacity by about 150 vphpl.

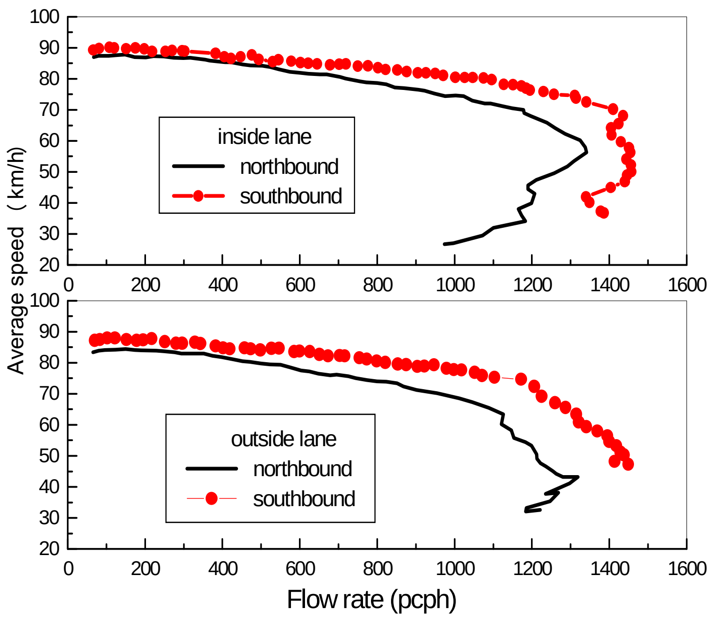


Figure 10. Comparison of flow-rate and speed relationship with southbound and northbound traffic in Sheasan tunnel

Figure 11 showed there was slight difference in the relationship between flow rate and speed of traffic flow in Pernsan tunnel before the congestion condition. However, the southbound traffic flow entered in congestion condition at a low flow rate. This phenomenon might be resulted from that there was no ramp near the northbound exit and there was a ramp near the southbound exit. The flow-rate and speed relationship in Shiding tunnel was similar to that in Pernsan tunnel.

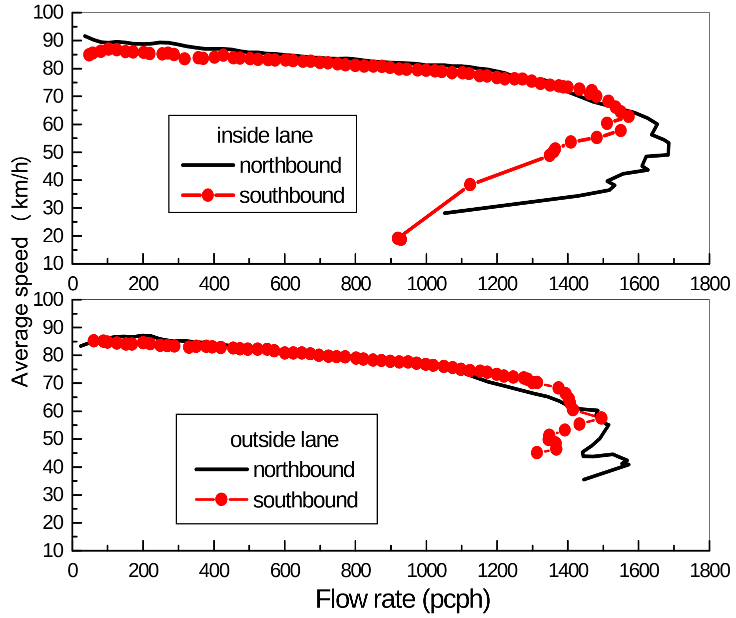


Figure 11. Comparison of flow-rate and speed relationship with southbound and northbound traffic in Pernsan tunnel

## 2.4 Capacity on Different Locations

Tables 1 to 4 showed the capacity and related critical speed (i.e. average speed when flow rate equals to capacity) in different locations of lengthways inside and outside lanes at different speed limits.

Table 1. Capacity and critical speed in different locations of northbound inside lane

| location | | speed limit (km/h) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 70 | | 80 | | 90 | |
| distance to the north-end of No.5 highway | Tunnel | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) |
| 0.706k | -- | 1390 | 50 | 1590 | 55 | -- | -- |
| 1.068k | Shiding | 1620 | 47 | 1560 | 56 | -- | -- |
| 3.198k | Shiding | 1430 | 42 | 1580 | 42 | -- | -- |
| 9.374k | -- | 1310 | 61 | 1560 | 67 | -- | -- |
| 9.840k | Pernsan | -- | -- | 1720 | 63 | -- | -- |
| 11.178k | Pernsan | 1490 | 42 | 1680 | 53 | -- | -- |
| 12.922k | Pernsan | 1490 | 64 | 1660 | 67 | -- | -- |
| 13.348k | -- | 1330 | 60 | 1570 | 59 | -- | -- |
| 14.800k | -- | 1010 | 68 | 1250 | 64 | -- | -- |
| 15.488k | Sheasan | 1050 | 51 | 1260 | 66 | 1310 | 72 |
| 20.055k | Sheasan | 1070 | 56 | 1300 | 52 | 1340 | 56 |
| 27.779k | Sheasan | 1190 | 64 | 1400 | 68 | 1440 | 71 |
| 28.420k | -- | -- | -- | -- | -- | 1470 | 72 |

Table 2. Capacity and critical speed in different locations of northbound outside lane

| location | | speed limit (km/h) | | | | | |
|---|---|---|---|---|---|---|---|
| distance to the north-end of No.5 highway | tunnel | 70 | | 80 | | 90 | |
| | | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) |
| 0.706k | -- | >1350 | <55 | 1590 | 49 | -- | -- |
| 1.068k | Shiding | >1620 | <45 | 1590 | 45 | -- | -- |
| 3.198k | Shiding | 1440 | 44 | 1570 | 42 | -- | -- |
| 9.374k | -- | 1270 | 59 | 1570 | 54 | -- | -- |
| 9.840k | Pernsan | -- | -- | >1520 | <55 | -- | -- |
| 11.178k | Pernsan | 1310 | 44 | 1510 | 40 | -- | -- |
| 12.922k | Pernsan | >1270 | <55 | 1490 | 49 | -- | -- |
| 13.348k | -- | 1220 | 54 | 1400 | 59 | -- | -- |
| 14.800k | -- | 930 | 64 | 1090 | 65 | -- | -- |
| 15.488k | Sheasan | 1030 | 49 | 1250 | 55 | 1280 | 55 |
| 21.055k | Sheasan | 960 | 40 | 1250 | 48 | 1260 | 50 |
| 27.779k | Sheasan | 930 | 65 | 1280 | 55 | 1260 | 72 |
| 28.420k | -- | -- | -- | -- | -- | 1220 | 71 |

Table 3. Capacity and critical speed in different locations of southbound inside lane

| location | | speed limit (km/h) | | | | | |
|---|---|---|---|---|---|---|---|
| distance to the north-end of No.5 highway | tunnel | 70 | | 80 | | 90 | |
| | | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) |
| 1.702k | -- | 1520 | 40 | 1610 | 62 | -- | -- |
| 3.178k | Shiding | -- | -- | 1480 | 64 | -- | -- |
| 3.506k | Shiding | >1174 | <69 | 1460 | 65 | -- | -- |
| 9.326 | -- | 1530 | 59 | >1530 | <72 | -- | -- |
| 9.840k | Pernsan | -- | -- | 1550 | 68 | -- | -- |
| 11.158k | Pernsan | 1460 | 59 | 1580 | 63 | -- | -- |
| 12.945k | Pernsan | 1460 | 59 | 1540 | 63 | -- | -- |
| 14.356k | -- | -- | -- | >1590 | 82 | -- | -- |
| 15.139k | -- | 1330 | 60 | 1540 | 68 | -- | -- |
| 15.478k | Sheasan | 1280 | 64 | 1450 | 71 | 1500 | 69 |
| 21.063k | Sheasan | 1230 | 54 | 1440 | 58 | 1470 | 58 |
| 27.442k | Sheasan | 1290 | 58 | >1530 | 57 | 1500 | 62 |
| 27.748k | -- | 1330 | 62 | >1550 | 63 | 1500 | 66 |
| 28.236k | -- | -- | -- | -- | -- | >1353 | <66 |

Table 4. Capacity and critical speed in different locations of southbound outside lane

| location | | speed limit (km/h) | | | | | |
|---|---|---|---|---|---|---|---|
| distance to the north-end of No.5 highway | tunnel | 70 | | 80 | | 90 | |
| | | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) | capacity (pcph) | critical speed (km/h) |
| 1.702k | -- | 1400 | 42 | 1610 | 62 | -- | -- |
| 3.178k | Shiding | 880 | 58 | 1470 | 58 | -- | -- |
| 3.506k | Shiding | >1310 | <64 | 1460 | 65 | -- | -- |
| 9.326 | -- | 1290 | 56 | >1530 | <72 | -- | -- |
| 9.840k | Pernsan | -- | -- | 1440 | 60 | -- | -- |
| 11.158k | Pernsan | 1300 | 58 | 1580 | 63 | -- | -- |
| 12.945k | Pernsan | 1270 | 53 | 1540 | 63 | -- | -- |
| 15.139k | -- | 1140 | 58 | 1540 | 68 | -- | -- |
| 15.478k | -- | 1160 | 58 | 1450 | 71 | 1560 | 53 |
| 21.063k | Sheasan | >1230 | <54 | 1440 | 58 | 1420 | 51 |
| 27.442k | Sheasan | >1270 | <54 | >1530 | 57 | >1550 | <55 |
| 27.748k | Sheasan | >1370 | <54 | >1550 | 63 | >1630 | 65 |
| 28.236k | -- | -- | -- | 1570 | 61 | 1630 | 65 |

## 3. CONGESTION ANALYSIS

### 3.1 Basic Sections

The congestion in a freeway section might be resulted from the traffic operation of downstream section, and the section with lower free speed often had lower capacity, so the location with significant decreased in free speed was the potential bottleneck of freeway No. 5. However, an essential condition of section congestion was high peak flow rate that the high peak flow rate was usually related to all-day flow rate. Therefore, this study analyzed the days when the all-day flow rate was higher than 37,000 vehicles between January and May of 2011.

According to the congestion condition, the northbound traffic operation of freeway No. 5 had the following characteristics:

1) During high flow-rate holidays, severe traffic congestion often occurred in the section from 18.313K in Sheasan tunnel to the upstream Toucheng interchange. The period of speed lower than 40km/hr in a day was sometimes as long as 10 hours. Toucheng entrance ramp (29.843K) and Sheasan tunnel entrance (28.134K) were potential bottlenecks. However, the first cause for lasting traffic congestion was that the bearable flow rate at 21.055K (near the midpoint of tunnel) and 18.313K was much lower than the flow rate entering Sheasan tunnel.
2) There was an off-ramp and an on-ramp between Sheasan tunnel exit (15.180K) and Pernsan tunnel entrance (13.263K). Generally speaking, the ramp was likely to cause congestion in peak hours. However, there was no severe traffic congestion in this section between January and May of 2011. This phenomenon might be resulted from the limited flow rate leaving Sheasan tunnel, and the flow rate from the on-ramp (14.583K) to the mainline seldom exceeded 800 vphpl. Therefore, the section near Pernsan tunnel entrance can bear the traffic flow from upstream mainline and on-ramp. If the entrance ramp flow rate kept increasing, there might be severe traffic congestion near Pernsan tunnel entrance and in upstream section.
3) There was no severe traffic congestion in Pernsan tunnel during January to May of 2011. The bearable flow rate near the midpoint of this tunnel (11.178K) was lower than that near the upstream entrance (12.922K). Therefore, around the midsection of the tunnel might influence the upstream traffic operation severely in high traffic flow condition.
4) There was an on-ramp at about 530m upstream to Shiding tunnel entrance (3.515K). When the traffic flows from on-ramp and mainline merged, the congestion often occurred at about 300m downstream to the tunnel entrance, and then the upstream was in congestion condition. If the entrance was congested long, the section near the tunnel entrance (0.798K) will be in congestion condition. The upstream and downstream of Shiding tunnel were mostly congested for 3 to 6 hours in a day during national holidays between January and May of 2011. However, the congestion condition seldom extended to upstream 7.636K.

According to the congestion condition, the southbound traffic operation of freeway No. 5 had the following characteristics:

1) Shiding tunnel and its upstream and downstream sections often had severe congestion on the days of high flow rate. The congestion duration under average speed less than 30 km/h in a day was mostly 4 to 9 hours. The primary cause for congestion was that the tunnel entrance (0.783K) was inable to carry the flow rate to

enter the tunnel. Another cause was that there was an off-ramp and an on-ramp within about 700m downstream to the tunnel exit (3.481K). Sometimes the congestion was confined to the upstream section of mainline and on-ramp (4.178K) merging area. However, sometimes the congestion in Shiding tunnel and nearby upstream section was influenced by the traffic congestion near the entrance of downstream Pernsan tunnel (9.063K).

2) The peak traffic flow kept accelerating after entering Pernsan tunnel, so the congestion situation in Pernsan Tunnel was not high.
3) There was an off-ramp and an on-ramp between Pernsan tunnel exit (13.303K) and Sheasan tunnel entrance (15.203K). Severe traffic congestion seldom occurred in this section during January to May of 2011. The first cause for this phenomenon might be the low flow rate from the on-ramp to the mainline, usually at 300 vphpl.
4) The peak traffic flow decelerated gradually after entering Sheasan tunnel (entrance at 15.203K). The minimum speed was near the midpoint of tunnel (21.063K). There was no significant change in the speed between 21.063K and 27.442K. However, the speed at 28.236K near the tunnel exit (28.127K) was significantly higher than upstream. The lane changing was allowed in the section near the tunnel exit. The lane changing might be the major factor for the low speed between 21.063K and 27.442K upstream. However, there was transient congestion occasionally at 21.063K between January and May in 2011, the southbound traffic flow in Sheasan tunnel usually kept the average speed above 50 km/h.

### 3.2 Mainline and On-ramp Merging Area

When a traffic flow from the ramp entered or leaved the freeway mainline, the traffic flow in the mainline is disturbed by the deceleration, acceleration and merging of the vehicles from the ramp. The degree of interference was especially high at the merging point of mainline and on-ramp. What mainline and on-ramp flow rates can cause congestion in the merging area was much cared by highway operating institutions. This study discussed this problem according to the four merging sections in Figure 12. The four merging areas excluded the section between Sheasan tunnel and Pernsan tunnel and the merging section of northbound on-ramp of Pinglin interchange and mainline. There was an off-ramp in the upstream of the on-ramp, but there was no detector between the two ramps, so the flow rate from the mainline to the merging area cannot be estimated.

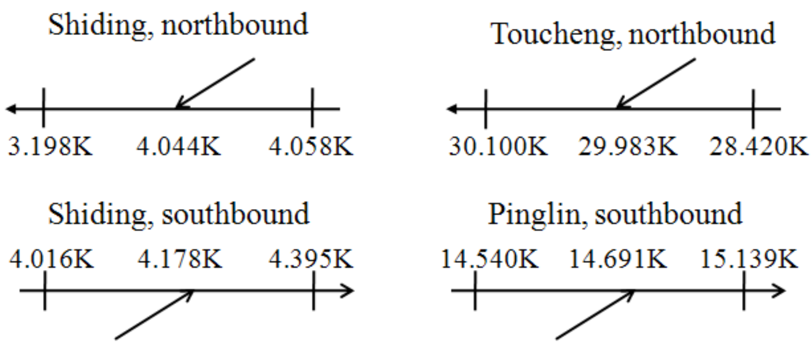


Figure 12. Schematic diagram of analyzed merging sections

The vehicle detectors failed to provide the flow rate data of northbound merging section on-ramp of Shiding tunnel and upstream mainline of the ramp between January and May of

2011, so this study used the data of 2010 to analyze the traffic characteristics of this section. The other three merging sections were analyzed by using the data of 2011. In addition, the vehicle collision in the merging section was mostly between the vehicles in the on-ramp and the vehicles in the outside lane of mainline, so the inside lane was excluded from the analysis.

Figures 13 to 16 showed the flow-rate and speed relationship when the traffic flow transited from stable condition to congestion condition on the outside lane of downstream mainline of various on-ramps in Figure 12. As seen, the outside lane flow rate of mainline might be lower than 600 vphpl at the beginning of congestion, and it might be higher than 1,300 vphpl. This phenomenon was resulted from the traffic flow from the ramp. According to the data provided by the detectors in different time intervals, Figure 17 showed the on-ramp flow rate and the flow rate in the outside lane of upstream mainline of the ramp before congestion. Moreover, the flow rate combination on the lower left of straight line was unlikely to cause the congestion of downstream traffic flow of the ramp. However, when the flow rate in the outside lane of upstream mainline of the ramp and the ramp mainline exceeded approximately 1,200 vphpl, the downstream mainline of the on-ramp might enter in congestion condition.

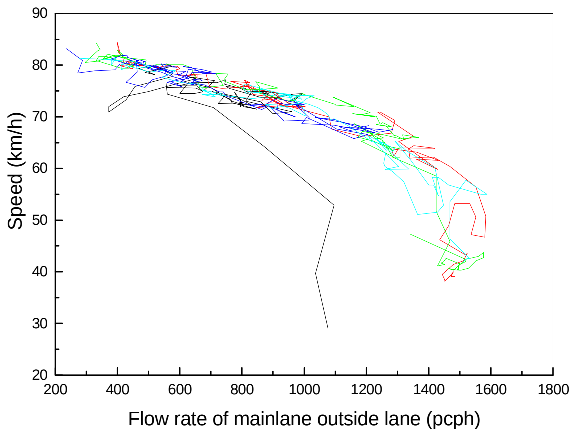


Figure 13. Flow-rate and speed relationship of mainlane outside-lane on downstream of Shiding northbound on-ramp

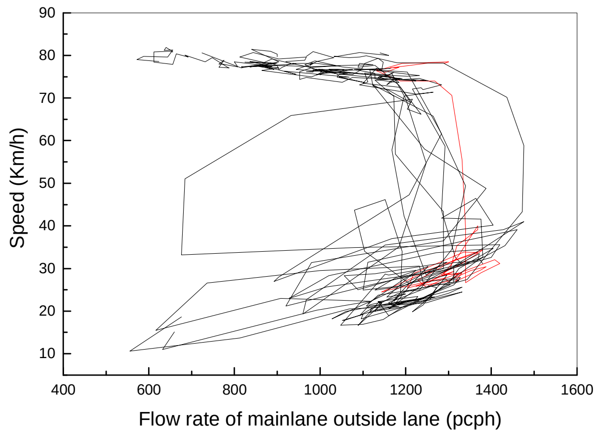


Figure 14. Flow-rate and speed relationship of mainlane outside-lane on downstream of Toucheng northbound on-ramp

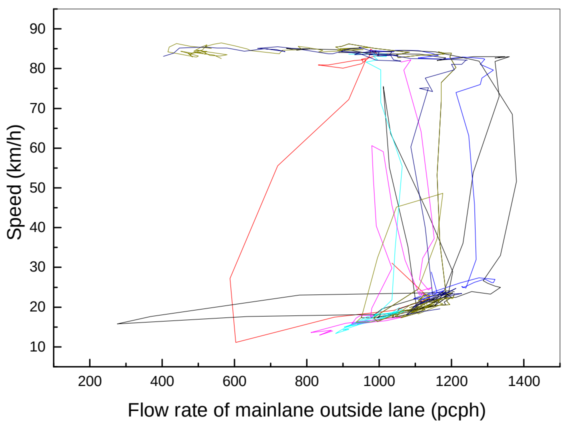


Figure 15. Flow-rate and speed relationship of mainlane outside-lane on downstream of Shiding southbound on-ramp

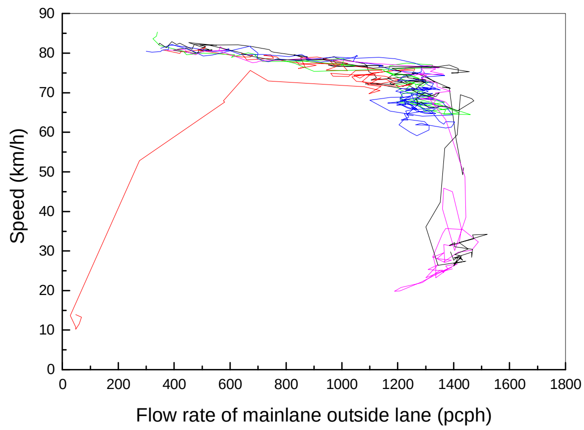


Figure 16. Flow-rate and speed relationship of mainlane outside-lane on downstream of Pinglin southbound on-ramp

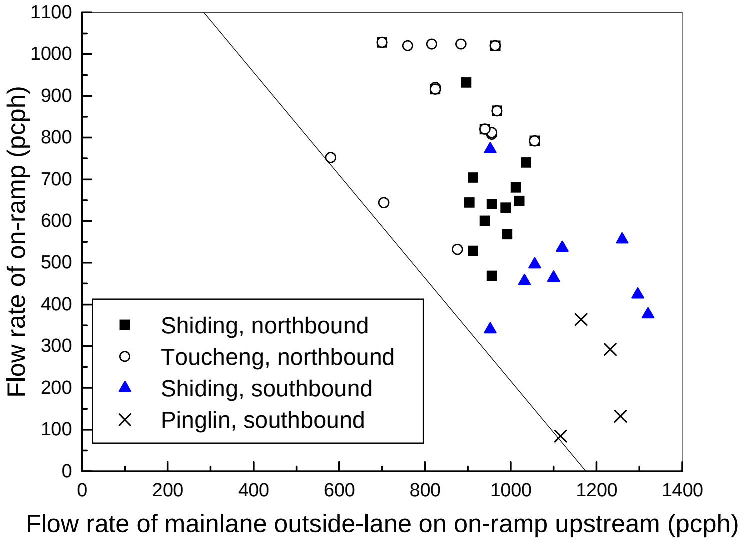


Figure 16. Flow rate of on-ramp and upstream mainlane outside-lane before traffic congestion

## 4. CONCLUDING REMARK

This study analyzed the traffic flow characteristics in various sections of the tunnel group freeway (Taiwan freeway No. 5), and indicated the locations with lower operation efficiency on this freeway. The main results and findings were described below:

1) The potential or common congested sections in tunnel-group freeway No. 5 included: the section from northbound Shiding tunnel entrance to its upstream 4km, the section from the midpoint of northbound Sheasan tunnel to the upstream Toucheng interchange (about 10km), and the section from the southbound Shiding tunnel to Pernsan tunnel (about 10km).
2) The capacity near the midpoint of northbound Sheasan tunnel was only 2,600 pcph (1,340 and 1,260 pcphpl on inside and outside lane respectively). The capacity near the northbound tunnel entrance was a little higher at 2,700 pcph (1,440 and 1,260 pcphpl on inside and outside lanes respectively). However, the discharge flow rate after the congestion at the entrance was higher than the capacity. As the capacity near the midpoint of the tunnel was insufficient, the shock wave transmitted upstream was likely to be caused during the holidays of high flow-rate, worsening the congestion at the tunnel entrance and upstream section.
3) The capacity of northbound Pernsan tunnel was about 3,150 pcph (1,660 and 1,490 pcphpl on inside and outside lanes respectively). Severe congestion seldom occurred in the northbound section from Sheasan tunnel exit to Pernsan tunnel. This phenomenon might be resulted from that the flow rate entering Pernsan tunnel was limited to the passable flow rate through Sheasan tunnel, and the flow rate from Pinglin interchange on-ramp to mainline was not high, so that the flow rate entering Pernsan tunnel seldom exceeded the capacity of Pernsan tunnel.
4) The capacity of northbound section of Shiding tunnel was about 3,150 pcph (1,560 and 1,590 pcphpl on inside and outside lanes respectively). As this tunnel entrance and upstream section were influenced by the traffic flow from the on-ramp near the tunnel entrance, severe congestion often occurred during holidays.

5) The capacity of southbound section of Shiding tunnel was about 2,950 pcph (1,480 and 1,470 pcphpl on inside and outside lanes respectively). The approximately 10km long section from this tunnel entrance to aroundthe midpoint of Pernsan tunnel was congested severely during holidays.
6) The capacity of southbound section of Pernsan tunnel was about 2,990 pcph (1,550 and 1,440 pcphpl on inside and outside lanes respectively). The southbound section and northbound section had the minimum capacity near the midpoint of Sheasan tunnel. The capacity of southbound section was 2,880 pcph (1,440 and 1,440 pcphpl on inside and outside lanes respectively), higher than the capacity of northbound section by 280 pcph. There was no severe congestion in the southbound section from Pernsan tunnel exit to Sheasan tunnel exit. One of the reasons was that the flow rate from Pinglin interchange on-ramp to the mainline heading for Sheasan tunnel was very low.
7) The highway mainline and on-ramp merging area was likely to be congested severely under high flow rate. The traffic flows in the on-ramps of Toucheng interchange and Shiding interchange often caused severe congestion. As the traffic flow in Pinglin interchange on-ramp between Pernsan tunnel and Sheasan tunnel was not large at present, there was not yet severe congestion. However, there should be a strategy for controlling the traffic flows in the entrance ramps on freeway No. 5 and other national freeway to achieve the best traffic operation efficiency. How to determine more good traffic control strategies were an important issue for freeway authority.
8) The logics for estimating the lane capacity and bottlenecks of tunnel-group freeway were the mainly contributions of this study. Because there were no simulation analysis or experiments on traffic control alternatives, this study could not measure the change of different strategies. The critical speed and volume in table 1 to 4 would be helpful for developing control strategies

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