COMPARATIVE TRAFFIC DATA ANALYSIS FOR A MOTORWAY WITH A TUNNEL SEGMENT

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Abstract

This paper introduces the changes of traffic characteristics in one of “Seoul-Chuncheon Motorway” sections including a tunnel segment in South Korea. It is easy to understand that the traffic characteristics are by no means a constant value and are dependent on geometrical features like a tunnel. It would be also important that the traffic characteristics could affect total travelling time passing the section and the results of a Cost-Benefit Analysis (CBA). Overall traffic characteristics such as free-flow speed, road capacity and breakdown effect were analysed for demonstrating this impact. The past one-year data from Korean Intelligent Transport System (ITS) clearly shows these changes in many locations inside and outside a tunnel.

Some meaningful values in the data analysis are suggested in this paper. The initial observation during the comparatively short period (45 days) derives the lowest free-flow speed and the largest traffic volumes through comparing with every value in each location. In the latter part of this paper, the detailed one-year data analysis minimises the errors, which are the impacts of external conditions such as season or weather. In addition, traffic volume at the breakdown point as well as free-flow speed and road capacity indicate that a tunnel could cause the changes in travelling time.

It is significant that the derivation of the various values from this analysis could guarantee the possibility of developing a new model for the traffic assignment in a motorway section that has similar geometry to that in this paper.

1. Introduction

Cost benefit analysis (CBA) has an important role on the governmental decision-making process for the major transportation infrastructure investment. As can be seen from the steps of CBA, they generally include the processes such as traffic demand forecast, cost and benefit calculation, economic analysis, financial analysis including public-private partnership, and overall estimation. Especially, the traffic demand forecast would be the fundamental process in CBA because it could affect the calculation of all the relevant benefits including travelling time savings, vehicle operating costs savings (KDI, 2008)[1]. However, the current assumption of traffic demand forecasting in Korean CBA is that all planned roads will have level terrain (KDI, 2015) even if 70% of Korean entire land is covered with mountains. In other words, the consideration of traffic assignment dependent on unusual road geometry could affect the result of CBA because it could prevent underestimated travelling time predictions.

The final aim of this study is to improve the accuracy of CBA by developing a new traffic demand-forecasting model considering a hilly road with a tunnel, which is one of the common characteristics in Korean motorway. The Volume Delay Function (VDF) reflecting them will be developed and be compared with theoretical one through finding the relationship statistically between traffic flows and travelling time. Eventually, this analysis can contribute to the more delicate traffic assignment in the traffic demand forecasting process of CBA.

For this, the impact factors that could affect VDF should be considered. When looking into widely used VDFs, all of the exponential (Smock, 1962), BPR (Bureau of Public Roads, 1964) and conical (Spiess, 1990) function have the correlation with free-flow speed and road capacity. The geometrical feature with a tunnel that could change these characteristics is not stated other than vertical slope in Korean Highway Capacity Manual (KHCM) by MLTM[2] (2013). Yun and Shengrui (2012) tried to find the lowest maximum traffic flow of “No. 3 Qin Ling Tunnel” from six locations during the unknown period near the tunnel by drawing the relationship between speed and density, not by observing the traffic volume directly. Koshi et al. (1992) showed the changes of vehicle’s movements in a tunnel through the relationship graphs among speed, traffic volume, departure flow and spacing without suggesting the unique value.

This paper investigates the values that could represent these basic traffic characteristics focusing on impact factors for VDF. The study uses the data from one-year Korean ITS on six locations in the selected motorway section In addition, the breakdown effect in a tunnel was examined for more detailed traffic characteristics derivation. The capacity is regarded as a constant value in traffic assignment process in Highway Capacity Manual (HCM) by Transportation Research Board (2000), but another definition of the breakdown observations in basic sections was demonstrated (Brilon *et al.*, 2005; Dong and Mahmassani, 2009; Kalaee, 2010). This concept could be applicable to a tunnel segment.

2. Case Selection and Data Collection

Korean motorway design

According to MLTM (2015), the design speed in a motorway (Table 2-1) is described as 120kph in a level terrain and 100kph in a mountainous terrain or an urban area (The operated speed limit is divided into 100kph or 110kph). With regard to the cross-section characteristics, every motorway generally has the minimum lane width of 3.50m and the minimum central barrier width of 3.0m in a rural area and 2.0m in an urban area. In addition, the minimum right lane clearance of 3.0m in a rural area and 2.0m in an urban area and the minimum left lane clearance of 1.0m in both areas. In spite of the clearance regulation, the minimum clearance in a segment where a structure such as a tunnel or a bridge exists would be deregulated into 1m. When looking at a longitudinal section, the maximum degree of slope in a motorway is ranging from 3% in a level terrain to 4% in a mountainous terrain in the case of the 120kph design speed and from 3% in a level terrain to 5% in a mountainous terrain in the case of the 100-110kph design speed (However, practically the slope in a motorway does not exceed 3% even if the road is located on a mountainos area). The minimum radius of the horizontal curvature in a motorway is ranging from 420m to 710m dependent upon the design speed and superelevation. Lastly, the unique regulation applied to the tunnel segment in Korea compared with other countries is that all vehicles are restricted from changing lanes (However, many vehicles tend to ignore this regulation).

[1] Korean Development Institute

[2] Ministry of Land, Transport and Maritime affairs

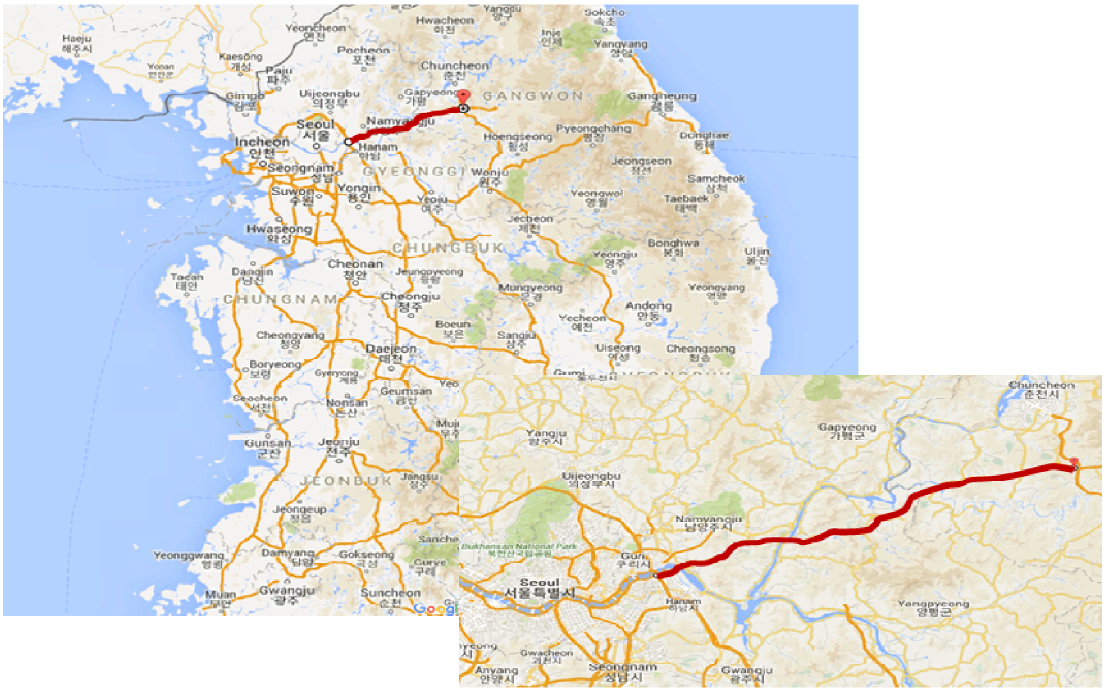
Table 2-1. Design Speed on Road category

Category		Design Speed (Km/h)		
		Rural Area		Urban Area
		Level Terrain	Mountainous	
Motorway		120	100	100
Other roads	Major Arterial	80	60	80
	Minor Arterial	70	50	60
	Collector	60	40	50
	Local	50	40	40

Case selection: "Seoul-Chuncheon Motorway"

The motorway route selected for this study is Seoul-Chuncheon Motorway (Figure 2-1), which was constructed in 2009 by public-private partnership. Seoul is the capital city of Korea and Chuncheon is one of the main cities in Gangwon Province, which is the eastern area of Korea. Gangwon Province has many attractive places for tourists, so many traffic passing through this route aims for the tourism and congestion would tend to happen on weekends or holidays. The total length of the motorway is 61.4km and nine interchanges including the starting and ending points. This road has 41 tunnels and 103 bridges because it penetrates mountainous terrain. The Average Daily Traffic (ADT) is 40,046 veh/day as of 2016, which is the traffic volume corresponding to four lanes by 12-hour observation. The enforcement speed limit of this route is 100kph. The number of lanes in this freeway is eight from the starting point to 1.9km, six from 1.9km to 14.9km, and four from 14.9km to the ending point (61.4km).

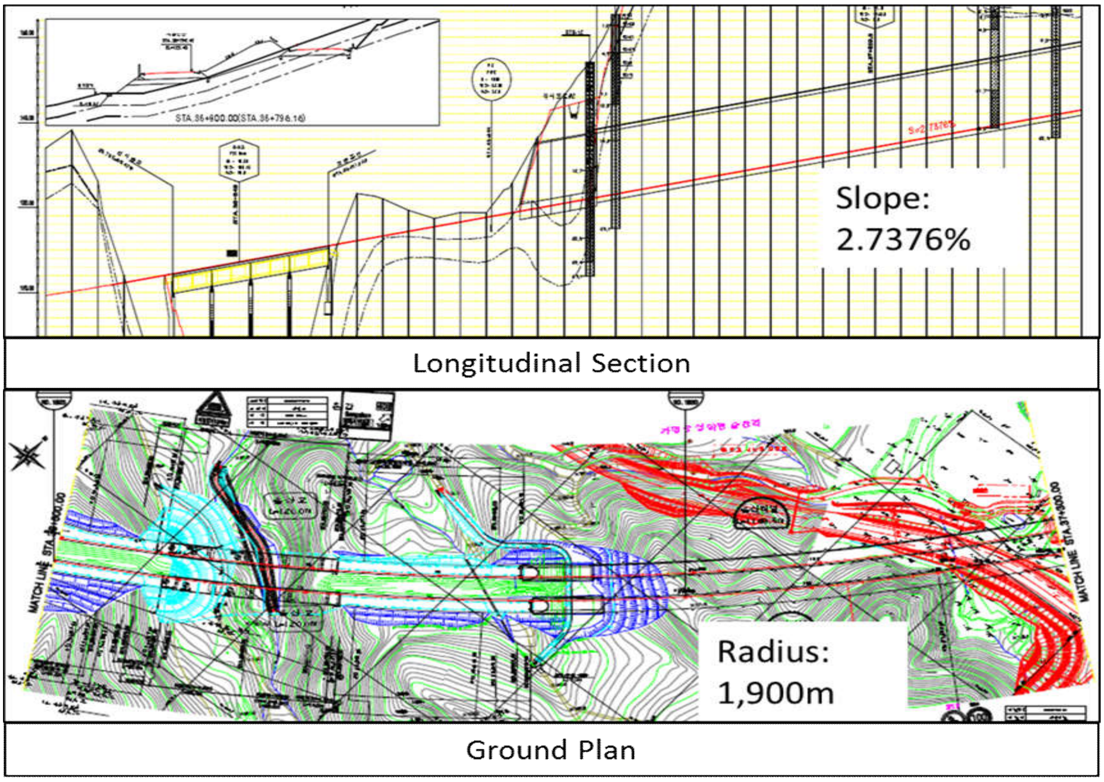
Figure 2-1 Case location



Geometrical features of the case

The case analysed in this study is the section to the east direction between 36.02km and 37.86km from the starting point in "Seoul-Chuncheon Motorway", which includes 'Songsan Tunnel'. The length of the tunnel is 1,135m, the degree of slope in the tunnel is 2.7376%, and the minimum radius of horizontal curve is 1,900m. Both of the open and tunnel segment has the lane width of 3.50m, but the clearance of 2.0m in the tunnel segment is shorter than that (3.0m) in the open segment. One of the reasons why this case is selected is that the case is known as a frequently congested route. The geometrical features would be in coincidence with this study, which has a hilly geometry and a comparatively long tunnel. Six inductance loop detectors (two outside and four inside the tunnel) observed traffic as mentioned later.

Figure 2-2. Design Map of the Case



Data collection

Korean Intelligent Transport System (ITS) is covering all the motorways to give the traffic information to road customers. Korea Expressway Corporation (KEC) is managing and operating most routes, but private companies is doing some routes. According to the document from KEC, the average distance between inductance loop detectors in all motorways is 1.8km, but the detectors are installed more closely in a frequently congested or tunnel section. The traffic information mainly produced by an inductance loop includes time, location, traffic volume, average speed and occupancy rate. The traffic data is produced every minute, but average traffic information data just before five minutes is stored in ITS main servers for five years without consideration of vehicle's types. The speed data is collected by averaging each vehicle's speed arithmetically for one minute, and then is finally served as a form of space-mean speed by averaging five one-minute time-mean speeds harmonically. The occupancy rate is made by recognising existing time on a loop, but the accreditation for the occupancy is not established in Korea and the accuracy would not be guaranteed. Therefore, it could be used only for confirming the congestion.

As mentioned earlier, the data for this paper was collected from six inductance loop detectors, whose characteristics can be seen from Table 2-2. Six detectors collected traffic information about vehicles passing through 1.84km section of this case. Two of the detectors are located before the tunnel entrance respectively with 840m and 310m and others of them are located in the tunnel with the approximate interval of 300m.

The data set for one year used in this paper was stored in ITS organised by the time and location (inductance loop ID). KEC was asked to extract the data from August of 2016 to August of 2017 and the data.

Table 2-2. Geometrical features with Inductance loop detectors' locations

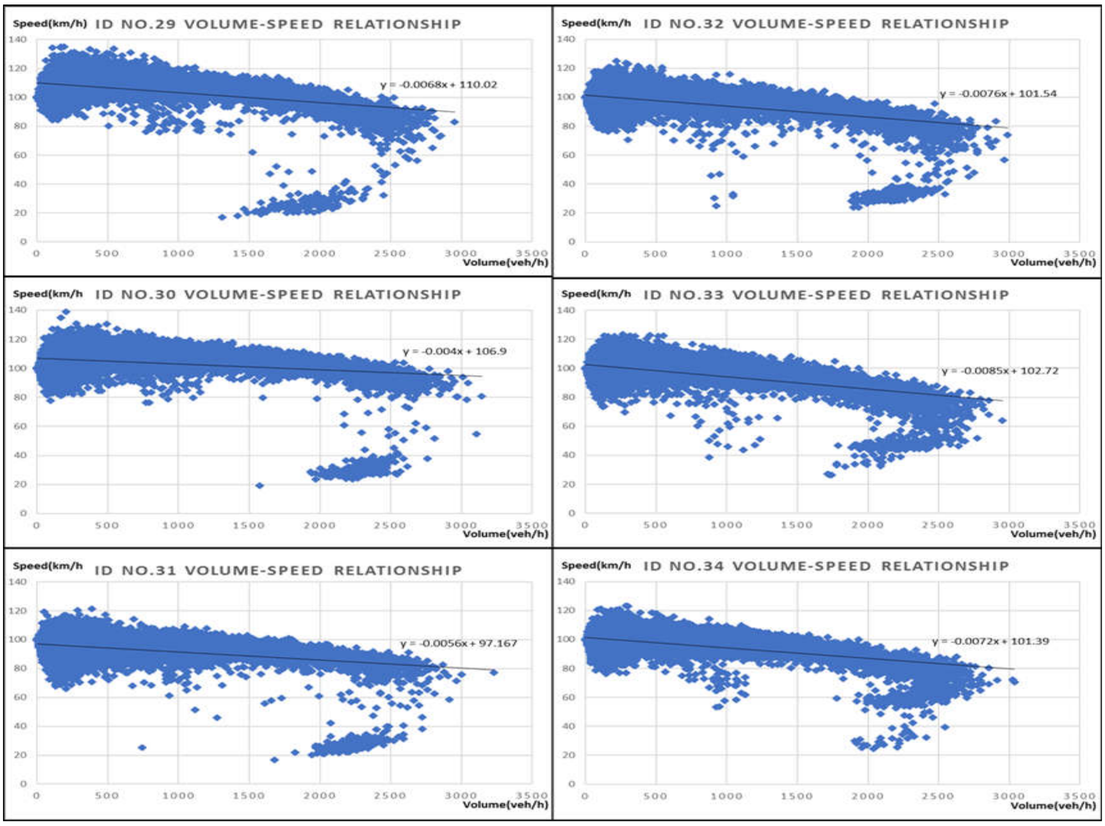
ID No.	Location	Distance from tunnel entrance	Slope	Reference
29	36.02km	840m* (before)	-0.78%	Outside the tunnel
30	36.55km	310m (before)	2.74%	Outside the tunnel
31	36.89km	30m (after)	2.74%	Inside the tunnel
32	37.19km	330m (after)	2.74%	Inside the tunnel
33	37.49km	630m (after)	2.74%	Inside the tunnel
34	37.86km	1,000m (after)	2.74%	Inside the tunnel

3. Initial Data Analysis

Overall analysis summary

Prior to the detailed analysis, the data from 5th of October to 18th of November in 2016 (45 days) was examined initially in this study because traffic observation in autumn seems to be the most reliable regardless of weather conditions. The number of data rows on each location is 12,787 and the relationships between the average traffic volume and speed on each location during this period were drawn. The initial data analysis could find the tendency of the relationship (Figure 3-1), which shows the pattern of the Greenshield's model typically. The graphs also present traffic characteristics in a tunnel segment such as the free flow speed, maximum traffic volume and breakdown effect.

Figure 3-1. Traffic volume-Speed Relationship on each location



Free flow speed

HCM (2000) defines free-flow speed as "the mean speed of passenger cars under low to moderate flow rates that can be accommodated on a uniform roadway under prevailing roadway and traffic conditions. In addition, it also suggests that free-flow speed for a motorway could be measured as a mean speed when the traffic volume is below 1,300 passenger cars per hour per lane (pcphpln). This means that the mean speed corresponding to the traffic below 2,600 passenger cars per hour (pcph) would become the free-flow speed. However, it could not be applied to this study because the level of traffic volume would already cause the congestion (Figure 3-1). Instead, Kalaee (2010) measured the free-flow speed as the average value of speeds corresponding to each traffic volume under 360kph vehicle per hour (vph). When this assumption applies to this study, the free-flow speed decreases from 106.6kph at ID No. 29 to 98.7kph at ID No. 34 and the minimum free-flow speed is recorded as 95.0kph just after the tunnel entrance (ID No. 31). This seems to be because most vehicles would decelerate their speed when they would approach to the tunnel entrance (Table 3-1). However, the speed increases in the middle of the tunnel and stayed steadily towards the end of the tunnel. This observation seems to result from vehicle's movements to adapt the environment of a tunnel.

Maximum traffic volume

As can be seen from the result in Road Traffic Survey (2016), Seoul-Chuncheon Motorway have the high percentage of passenger car occupancy (81.9%) compared with other motorway routes having the percentage with around 70% because there are many vehicles for tourism as early mentioned. ITS for Korean motorways currently does not serve the data about vehicle's length even if inductance loop detectors can recognise the length between axes. Therefore, this paper can illustrate the analysis about the traffic volume irrelevant to vehicle's types.

HCM (2000) defines that the motorway capacity is the maximum number of passenger cars per hour for 15 minutes in a representative motorway segment. The maximum traffic volume would the closest definition to the motorway capacity even if it does not seem to fit for the definition perfectly because it is not the value considering any factors such as heavy vehicles percentage on the observation time. The maximum volume from this initial data analysis for 45 days in this section is 3,228vph at ID No. 32 (Table 3-1). The maximum traffic volumes based on 15-min aggregated observation are compared with the theoretical road capacity (Table 3-1). According to MLTM (2013), the theoretical road capacity in this study case, whose characteristics are 120kph design speed, 2 lanes to each direction, 3.5m lane width, 1.0m left clearance, 2.0m right clearance, 20% heavy vehicles percentage and hilly terrain, is calculated as 3,200pcph. The maximum 15-min traffic volume (2,948vph) in this section is lower by 9% compared with 5-min one (3,228vph) and it would be also lower by 8% than the theoretical road capacity (3,200pcph) even if the heavy vehicles percentage in this study is not considered.

Table 3-1. Observation of Free-flow Speed and Traffic Volume (5-min and 15-min observation) on Locations

ID No.	Free-flow Speed (kph)	Max. Traffic (vph) (5-min traffic *12)	Max. Traffic (vph) (15-min traffic *4)	Theoretical road capacity (pcph)
29	106.6	2952	2708	3200
30	103.9	3144	2948	
31	95.0	3228	2836	
32	98.3	2988	2740	
33	99.3	2952	2720	
34	98.7	3036	2772	

Note: shadow cells are the minimum free-flow speed or the maximum traffic volume on all the locations

Comparison with data on each location

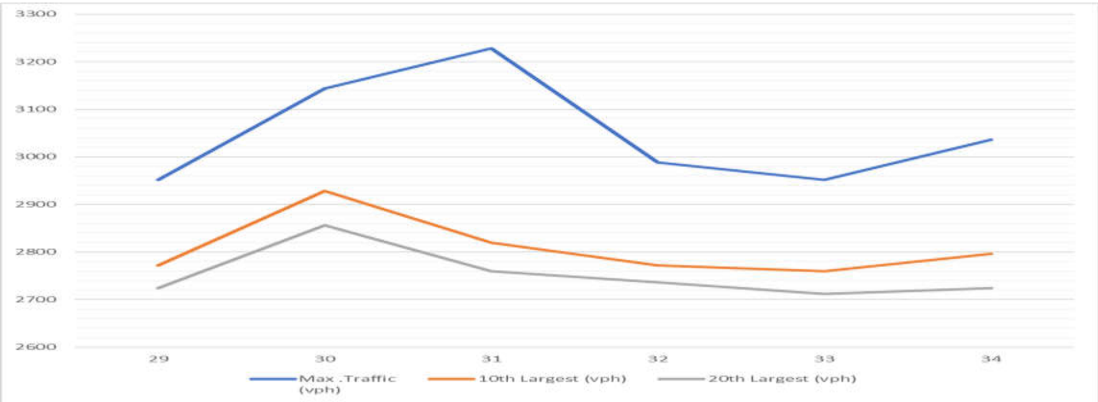
Another notable finding would be from comparison with the values on each location. As free-flow speed on each location decreased, the traffic volume (vph) on that location dropped accordingly (Table 3-2, Figure 3-2). This means that the tunnel is affecting the reduction of road capacity with free-flow speed, which was defined as a virtual bottleneck whose geometric features have no changes such as the decrease of the number of lanes (Brilon *et al.*, 2005). All of the maximum, the 10th and 20th largest traffic volume tend to decrease as the traffic volume happens inside the tunnel (Table 3-2). Compared with the value at ID No. 30 where is located on 310m before the tunnel entrance (Table 2-2), the value of each location is lower by 4%-6%. The reason why the 10th and 20th largest value as well as the maximum one was analysed in this study is that many factors including the heavy vehicles percentage are not considered.

Table 3-2 Comparison of Traffic Volume (based on 5-min observation) among Locations

ID No.	Max .Traffic (vph)	Comparison with No.30	10th Largest (vph)	Comparison with No.30	20th Largest (vph)	Comparison with No.30
29	2952	93.9%	2772	94.7%	2724	95.4%
30	3144	100.0%	2928	100.0%	2856	100.0%
31	3228	102.7%	2820	96.3%	2760	96.6%
32	2988	95.0%	2772	96.3%	2736	95.8%
33	2952	93.9%	2760	94.7%	2712	95.0%
34	3036	96.6%	2796	94.7%	2724	95.4%

Note: shadow area indicates locations inside the tunnel

Figure 3-2 Comparison of traffic volumes on locations



4. One-year Data Analysis

Overall analysis summary

For the detailed analysis, the data for one year from 22th of August 2016 to 2017 was examined. This analysis could reduce some result distortions by the traffic changes dependent on seasonal or weather conditions, and one-year observation would be effective on improving the possibility of lowering the heavy vehicles percentage because this data analysis is mainly interested in large values. The number of data rows is 105,489 on each location and this analysis is based on time series, which is different from the initial data analysis that is based on the relationship only between the values of traffic volume and speed. This data analysis by the time is necessary to clarify the impacts by breakdown. At this step, the traffic volume-speed relationship would be not significant because the graphs are aggregated by too many data rows.

Maximum road traffic

Figure 4-1 shows the comparison of the maximum traffic volumes on each location for 45 days and one year. The order of the maximum traffic volumes for one year on each location would be almost same as that for 45 days even if the difference between locations became small for one-year observation. The highest maximum traffic volume based on 15-min observation for one year in the selected section, which is the closest definition with abovementioned theoretical road capacity, is 2,948vph. In addition, the road capacity drop, which is close to the difference of the one-year maximum traffic volumes between the highest and lowest location, would happen by around 7% in this tunnel. Through one-year data analysis, the capacity drop in the tunnel would be verified with the 45-day data analysis and this finding could demonstrate that the virtual bottleneck would exist in the middle of the tunnel.

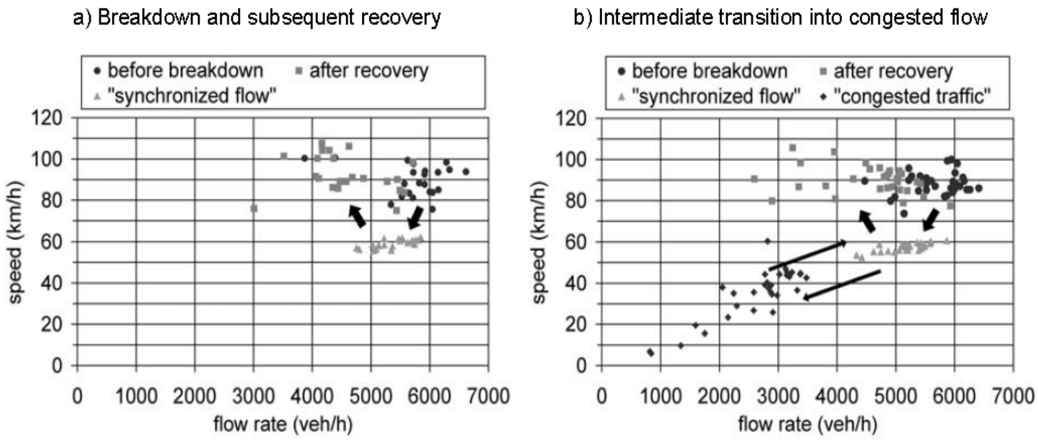
Table 4-1 Comparison of Maximum Traffic Volume between 45-day and 1-year data

ID No.	45-day Traffic (5 mins)		45-day Traffic (15 mins)		1-year Traffic (5 mins)		1-year Traffic (15 mins)		Theoretical road capacity (pcph)
	Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio	
29	2,952	91%	2,708	92%	3,156	98%	2,872	97%	3200
30	3,144	97%	2,948	-	3,216	100%	2,948	-	
31	3,228	-	2,836	96%	3,228	-	2,836	96%	
32	2,988	93%	2,740	93%	3,048	94%	2,872	97%	
33	2,952	91%	2,720	92%	3,096	96%	2,748	93%	
34	3,036	94%	2,772	94%	3,132	97%	2,820	96%	

Breakdown effect

Breakdown as well as free-flow speed and road capacity is an important consideration in this study because it could have an influence on overall travelling time in CBA. Brilon *et al.* (2005) defined that "Breakdown" happens by the significant speed drops of most vehicles causing from smooth to congested traffic flow and they mentioned that it could differ dependent on each driving environment. In addition, they explained the motorway breakdown dynamics, which is transition during breakdown and recovery in congested and uncongested situations (Figure 4-1).

Figure 4-1 Breakdown Dynamics during breakdown and recovery (German motorway)



Source : Brilon *et al.* (2005)

The breakdown effect in the tunnel is explained through three graphs (Figure 4-2) extracted from Figure 3-1. Every location seems to have the breakdown effect even if the frequency and the difference would be various with each other. As can be seen from Figure 4-2, the gaps of data points on each location between an uncongested and a congested situation are different; especially the gap inside the tunnel is smaller compared with that outside the tunnel. Likewise, as the data is measured at the end of the tunnel, the breakdown effect seems to be more unclear. On the other hand, the speed plots in congestion, which could be calculated in Figure 4-2 as an approximate average from 20 to 40kph, are rarely dense at ID

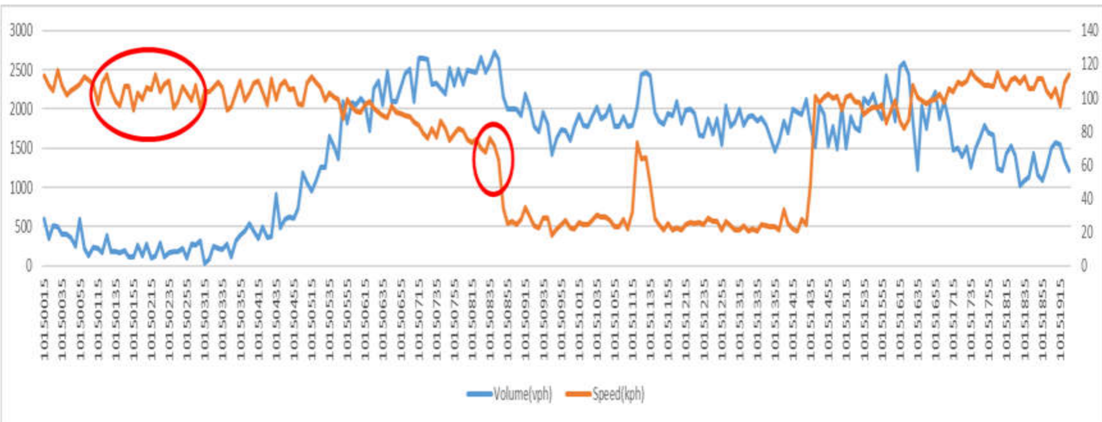
No. 34 (in the end of tunnel) and it could be related with this breakdown effect and the virtual bottleneck point. However, it is necessary that this analysis should be verified by more scientific and statistical methodology as well as by longer period data.

Figure 4-2 Breakdown Effect on Locations

Traffic volume on breakdown

The breakdown effect in the case of this study would be necessary to confirm, and the random sampling before and after congestion time at ID No. 29 was implemented (Figure 4-3). The breakdown happening on Saturday in 15th of October 2016 was observed after the state of free-flow earlier than this time. The speed drop at the breakdown point was checked and the traffic volume around this point peaked at the maximum. The congestion for over 3 hours at this location was also observed with the speed of around 20kph after the breakdown.

Figure 4-3 Traffic flow and speed changes in congestion



The breakdown point could be defined differently dependent on many factors such as countries or road types, but the common traffic characteristics at the point of breakdown would be three (Brilon *et al.*, 2005; Dong and Mahmassani, 2009; Kalaee, 2010). One is considerable speed drop, another is appropriate lower speed compared with the free-flow speed, and the other is some minute's duration with the lower. However, these three characteristics do not seem to be apparently suggested in the literature. Brilon et al. (2005) suggested that the threshold speed at the breakdown point would be 70kph in German motorway conditions and other considerations were implemented by using "Product Limit Method". On the other hand, Kalaee (2010) adopted the speed drop of 10mph between consecutive intervals and the lower speed than 55mph (88kph) in the US highways, which have free flow speed of 65mph.

In order to find the traffic volume at the breakdown point in this case, 5-min average speed data for one year was examined because the breakdown point analysis should focus on instantaneous traffic changes as much as possible. The threshold low speed of 70kph, the considerable speed drop of 16kph and the low speed (70kph) duration time of 15mins were applied for this study based on the above literature review. The 55mph (88kph) threshold low speed that Kalaee (2010) suggested seems to be too high to apply to Korean motorway. If it would be set too high, the wrong breakdown point could be caught in the process of applying the condition to entire data. The reasonable low speed setting in the breakdown analysis would be very important because high average speed with temporarily high traffic volume might not cause breakdown. The conditions for this analysis selected the combination of the low speed of 70kph applied to German motorway, the speed drop of 16kph applied to US motorway breakdown and 15-min duration. Later, the series of conditions would be applied to this analysis and then the adequate one for this case needs to be developed and verified.

The maximum traffic volume and the average of 10 largest traffic volumes among breakdown points on each location are represented with the maximum traffic volume in Table 4-2. The difference with the maximum traffic volume, which is close to road capacity, and the breakdown traffic volume on each location is remarkable. In addition, the drop of breakdown traffic volume in the middle of tunnel is also significant by 8% compared with that of maximum traffic volume by 5%.

Table 4-2 Traffic Volume at the Breakdown Point on Locations

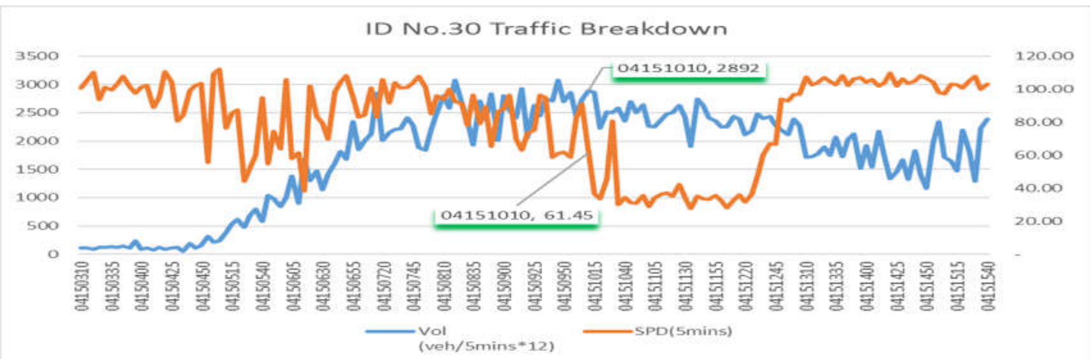
ID No.	Max. Traffic (5mins)		Max. Traffic among BPs		Avg. of 10 Largest Traffic in BPs	
	Value (vph)	Ratio*	Value (vph)	Ratio*	Value (vph)	Ratio*
29	3,156	98%	2,688	89%	2,570	92%
30	3,216	100%	2,892	95%	2,789	-
31	3,228	-	3,036	-	2,788	-
32	3,048	95%	2,880	95%	2,749	99%
33	3,096	96%	2,796	92%	2,575	92%
34	3,132	97%	2,844	94%	2,512	90%

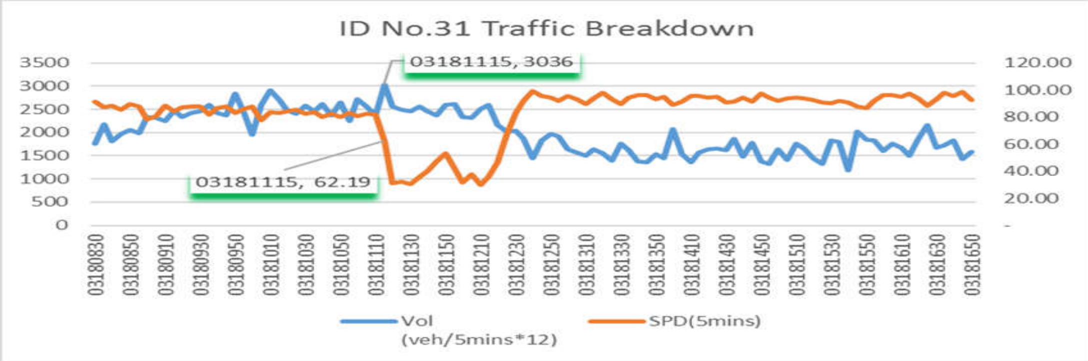
Note: BP: Breakdown Point, Ratio: The percentage with the maximum value

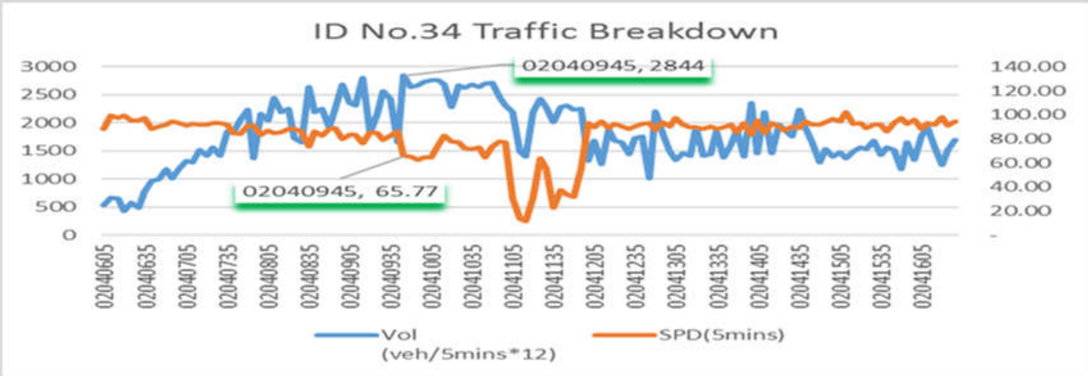
Observation of Breakdown Process

The traffic changes for some time near the breakdown time corresponding to the maximum of breakdown traffic volume were observed at ID No. 30, 31, 34 (Figure 4-4). The breakdown traffic volume at ID No. 30 is lower than the maximum traffic volume for the time, but the value at ID No. 31 and No. 34 is same as the maximum traffic volume for the time. Moreover, similar with Figure 4-2, the overall speed drops recorded at the breakdown points at ID No. 30 (outside the tunnel) are outstanding compared with those at ID No. 34, and the number of breakdown points with 176 at ID No. 30 (outside the tunnel) is much larger than that with 64 at ID No. 34 (in the tunnel). The total time between the breakdown and recovery would be different dependent on the traffic demand during the period, e.g. around 2 hours at ID No. 30 and just 20 minutes at ID No. 34.

Figure 4-4 Traffic Changes near the Breakdown Time on Locations







5. Conclusion

Traffic characteristics in a motorway tunnel, which appear differently from those in a basic segment, would make it a serious consideration necessary to make a decision about road projects including tunnel segments. As a result of inductance loops data analysis in the case of this study, which includes two locations outside the tunnel and four locations in a tunnel segment, the traffic characteristics in a tunnel seem to become more clear. This comparative analysis provides a more tangible understanding of the traffic characteristics in the selected case. The significant results in this study could summarise mainly four parts; the observation of traffic pattern for 45 days by using the Greenshield's model, the changes of free-flow speed before and after the tunnel, the difference of road capacity, and the variation of traffic volume and speed at the breakdown point for one year.

The curves of the relationships between traffic volume and speed for 45 days indicate that the tunnel environment in the selected case affected the traffic characteristics. The decrease of free-flow speed and the maximum traffic volume in the tunnel was observed initially. In addition, a gap in the data points from an uncongested to a congested situation was found and this became narrower towards the end of the tunnel. This demonstrates that the virtual bottleneck would exist in the middle of the tunnel as well as the breakdown frequency suggested in the end of this study.

It is clear that the average free-flow speed became reduced just after the tunnel entrance, even if this phenomenon is empirically widely known as a fact. The free-flow speed drop in the case is 11.6kph, whose lowest speed was recorded just after the tunnel entrance. Although correlation between the free-flow speed drop and road capacity decrease was not considered in this study, the speed drop will definitely affect the measurement of the total travelling time in this study later.

The road capacity decrease inside the tunnel was examined through 15-min aggregate observation for one year. The 1-hour equivalent traffic volume based on this observation demonstrates that the road capacity decrease has 200vph (7%) compared with the road capacity before the tunnel entrance and 452vph (14%) compared with the theoretical road capacity[3].

Lastly, the reduction of traffic volume at the breakdown point inside the tunnel was analysed through 5-min detailed observation. The percentage of the volume drop measured between the breakdown points was recorded as 8%. The traffic volume at the breakdown point will be used more importantly in this study because it would be the realistic standard causing congestion for predicting travelling time when taking account into traffic demand.

In addition to these facts suggested in this paper, it would be expected that vehicle's movements in a tunnel could be different from those in a basic segment. These changes of traffic characteristics in a tunnel will have an influence on the total travelling time of vehicles passing the road section. For the future study, the methodology for measuring travelling time more accurately among inductance loop detectors should be developed. Moreover, the cause-and-effect relationship between these traffic characteristics and the feasibility (e.g. CBA) of the road projects as well as between the geometrical features and traffic characteristics would be verified to obtain the aim of this study.

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[3] The comparison with the theoretical road capacity is by assumption that the measured traffic consists of only passenger cars.