Australasian Transport Research Forum 2022 Proceedings
28-30 September, Adelaide, Australia
Publication website: http://www.atrf.info

What causes slow-down on two-way two-lane expressways?

Jian Xing [1], Hidenori Goto [2]

[1] Nippon Expressway Research Institute Co., Ltd.

[2] Oriental Consultants Co., Ltd.

Email for correspondence: xing@ri-nexco.co.jp

Abstract

Two-way two-lane (TWTL) expressways account for approximately 30% of entire expressway network in Japan. Due to financial constraints, TWTL expressways cannot be timely widened and, therefore, heavy traffic congestion is usually seen in TWTL sections with high traffic demand. Lack of traffic detectors makes it difficult to analyse traffic flow characteristics and evaluate the operational performance on TWTL expressways. Recently ETC 2.0 probe data can be used to do the analysis and evaluation. This paper aims to analyse the factors causing slow-down from various angles by using ETC 2.0 probe data from all the 78 TWTL expressways in Japan. The study found that slow-down tends to occur immediately downstream of the end of passing lane, and in confined spots due to sag and some uphill slope, as well as tunnels and other road structures. The factors causing local slow-down in sections of downstream passing lane, sag and uphill slope, and tunnel are analysed in detail from different points of view in this study. The results can be used to identify the location of decline in and help improve operational performance and to review installation guidelines of passing lanes on TWTL expressways.

1. Introduction

The Japanese government has announced its policy for promoting 'smarter' use of two-way two-lane (TWTL) sections of expressways in Japan by effectively adding an auxiliary lane, etc., to mitigate slow-down on TWTL expressway sections, which account for approximately 30% of the total expressway length in Japan (1). It is suspected that some of the TWTL expressway sections are not functioning well as traffic arteries due to road structures and alignment, and implementation of effective measures is urgently called for to make such sections 'smarter'. However, it is also suspected that slow-down due to road structures, etc., is occurring in confined spots, in which case, conventional analysis techniques based on data obtained by vehicle detectors placed at regular space intervals would not be suitable, as they do not provide sufficient spatial resolution.

On the other hand, probe car data, especially those on expressways, are becoming increasingly available with the increasing penetration of such data collection systems as ETC 2.0. ETC 2.0 data of a vehicle contain its travel history captured at every 200 meters and a record of unusual driving behaviour that exceeded certain limits. Although ETC 2.0 data are samples and do not represent the travel history and driving behaviour of all vehicles, they provide temporal and spatial sequence data, which cannot be captured by conventional vehicle detectors, thus allowing road managers to identify spots, at which slow-down and/or aberrant driving behaviour occur, more easily than conventional techniques. In this study, vehicle travel history data are used to analyse the causes of slow-down on TWTL expressways in Japan.

This paper aims to analyse the factors causing slow-down from various angles based on analyses of ETC 2.0 probe data on the effects of providing an auxiliary lane to TWTL expressways towards their ‘smarter” utilization.

2. Literature review

Studies relating traffic flow characteristics and traffic capacity, operational performance, quality of service, etc. with TWTL highways have been widely conducted so far, e.g. (2-9). The representative one is the Highway Capacity Manual (HCM) (2). However, similar studies about TWTL expressways in Japan were limited although TWTL expressways account for approximately 30% of entire expressway network. Due to financial constraints, TWTL expressways cannot be timely widened and, therefore, heavy traffic congestion is usually seen in TWTL sections with high traffic demand. Some researches about traffic capacity of TWTL expressways have been conducted by Yoshikawa et al. (10, 11) and Shiomi et al. (12). Quality of service about traffic flow on TWTL expressways has not been conducted so far in Japan except some studies by Utsumi et al. (13), Catbagan et al. (14) and Nakamura et al. (15). This is partly because most of TWTL expressways have only one or even no vehicular detector between neighbouring interchanges to obtain traffic flow data necessary for analysis. Recently with the increasing penetration of ETC 2.0 service in Japan, ETC 2.0 probe data have been widely utilized to analyse bottleneck phenomenon, travel time reliability, route choice behaviour, incident detection and black spot identification, and so on (e.g. 16-18). In particular, traffic flow characteristics such as spot speed and spatial speed profile and quality of service of TWTL expressways have been intensively studied with ETC 2.0 probe data by Narushima et al. (19) and Kasai et al. (20). Narushima et al. (19), however, have only analysed three TWTL expressways (sections). This paper targets all the TWTL expressways in Japan including the three sections that have been analysed by Narushima et al. (19).

3. Methodology

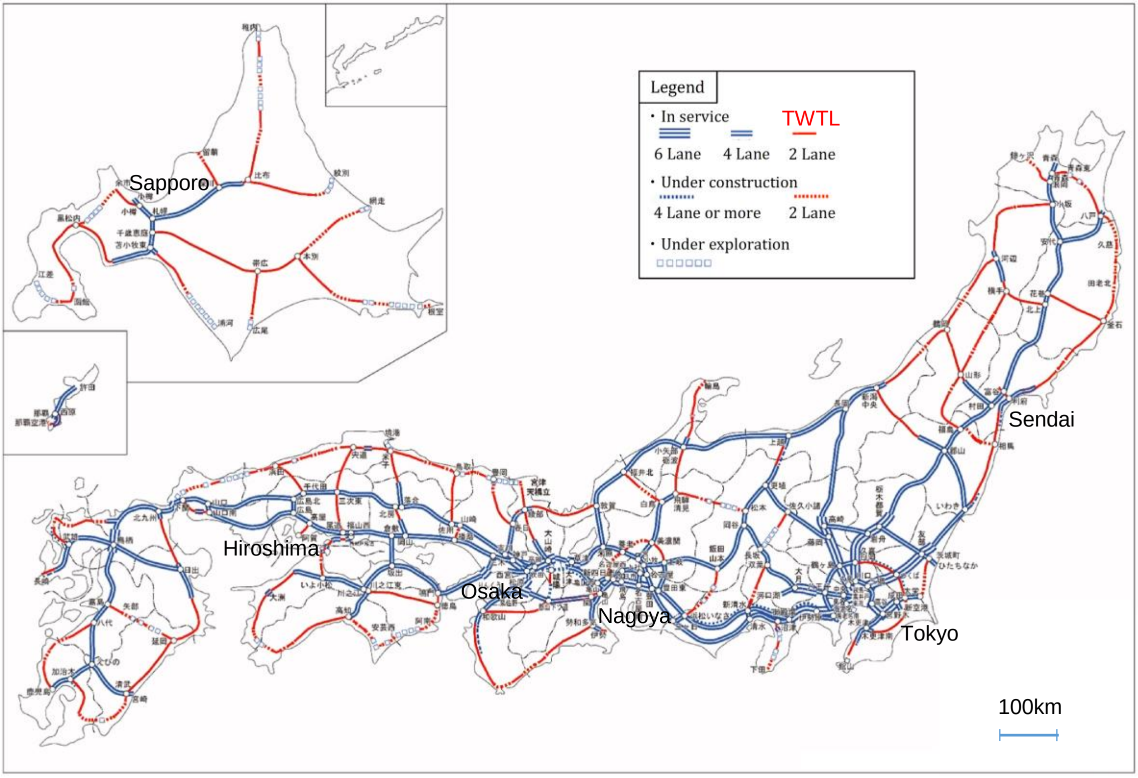
3.1. Data used for analysis

Travel history data recorded by ETC 2.0 service are used to analyse the traffic flow patterns on TWTL expressways. ETC2.0 is a service that utilizes bidirectional communication between roads (roadside units) and vehicles (onboard units) in order to provide a broader scope of information and to better support driving safety than conventional services such as ETC (electronic toll collection). As of 1 April 2018, roadside units (RSUs) have been installed at roughly 1,700 locations along expressways and at roughly 2,000 locations along national highways under direct government control throughout Japan. Along expressways, this service provides a broader range of information than before, including dynamic route guidance corresponding to road conditions at the time, images of upcoming areas with obstacles, and information to support driving safety where accidents frequently occur. In addition, vehicles equipped with ETC2.0 service compliant onboard units (OBUs) accumulate a “travel history” and “behavioral history” in a privacy-protected format. This information, which is widely used by road traffic authorities, is collected as probe data when these vehicles pass under an RSU. The travel history data includes vehicle ID, vehicle type, time, latitude and longitude. It is recorded every time a vehicle moves 200 m or 45 degrees, from the point where the previous data was recorded. But data within approximately 500 m from where the engine was turned on or off is not recorded from the viewpoint of personal information protection. The travel history data can be used to identify the locations of bottleneck and queue. On the other hand, the behavioral history data is point data such as vehicle ID, time, latitude / longitude, road type, longitudinal and lateral acceleration / deceleration, and yaw angular velocity. These data are recorded when any of the absolute peak values of longitudinal and lateral acceleration / deceleration exceeds 0.25g or when the absolute value of yaw angular velocity exceeds 8.5 deg/sec. The behavioral history data helps identify where sudden braking (rapid deceleration) frequently occurs. These data can be used to identify near-miss incident locations and to plan traffic safety measures.

Although ETC 2.0 probe data provides position data as to where the vehicles have travelled in latitude and longitude, it is not easy to locate the positions on a map. To facilitate the work, route names, kilometer posts (kp) showing the distance from the start of each expressway, and other information associated with the expressways based on a digital road map (DRM) are added into ETC 2.0 probe data prior to the analysis so that the movement and positions of vehicles can be captured more easily. For detailed information about attaching route information, please refer to the paper by Narushima et al. (19). Travel history data of a vehicle attached with route information are also linked to the traffic volume (15-minute flow rate) obtained by vehicle detectors based on the travel date and time of the vehicle so that the correlation between traffic flow and speed can be analysed.

The ETC 2.0 data used in this study comprise those collected over a one-year period between November 2015 and October 2016. The subjects of the analysis consist of all sections of the 78 TWTL expressways all over Japan with a total length of about 2,300 km as shown in Fig. 1.

Figure 1: Locations of TWTL expressways in Japan as shown in red solid line



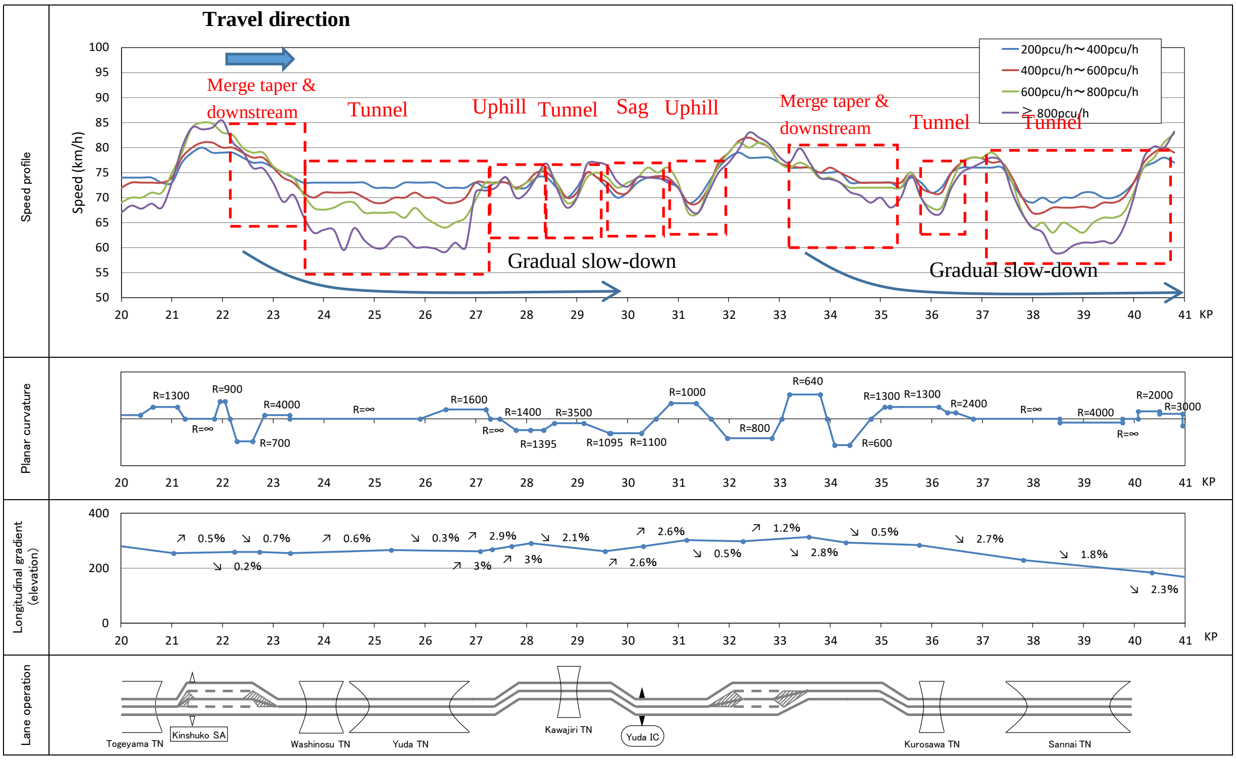
Overtaking is not possible in basic sections of TWTL expressways in Japan, as lanes are divided by rubber poles or other obstacles. For this reason, vehicles, which want to travel faster, have to use an auxiliary passing lane provided at 6 ~ 10 km intervals to pass slower-travelling vehicles. Auxiliary passing lanes are designed with the aim to enable faster vehicles that pass slower vehicles to continue travelling at their desired speed after returning to a TWTL section, thus improving the level of service of traffic flow in the sections of TWTL expressways. Accordingly, it is important to examine the speed profile to see how long a vehicle can maintain its desired speed from the end of an auxiliary lane. Speed profiles are produced for this purpose.

Speed profiles are drawn for different traffic flow levels divided in 200 pcu/h increments so that speed variation in relation to varying traffic flow can be analysed. Since the purpose of the study is to identify areas where an expressway's functionality declines due to slow-down, the 15th percentile value of the area speed is used as a reference base on the assumption that a vast majority (85%) of vehicles travel faster than that speed. In case the reference base needs to be changed to the average speed or 50th percentile, the 15th percentile value can be adjusted accordingly based on the observation data. The passenger car unit value (pcu) for large vehicles is set at 2.0 in this study.

3.2. A typical speed profile plotted from ETC 2.0 probe data

Fig. 2 shows a speed profile of the Kitakami-nishi ~ Yokote section of the Akita Expressway (outbound) that has a series of tunnels. The profile shows local slow-downs on uphill slopes around 28 kp and 31 kp and in a sag section around 29.5 kp, suggesting that the slow-down is caused by longitudinal gradients. When a large vehicle is followed by other vehicles on an uphill slope, the climbing performance of the following vehicles is forced to decline, as they cannot pass the leading vehicle. Slow-down in sags is considered to be caused by a phenomenon similar to the occurrence of a series of breakdowns in flow at a TWTL bottleneck such as sags and tunnels, etc., where small disturbances in speed occur within a platoon, leading to amplification and propagation of deceleration waves upstream (10, 11).

Figure 2: The 15th percentile speed profiles of Akita Expressway (Kitakaminishi – Yokote)



In addition, slow-down occurs in the tunnels of Washinosu around 24 kp, Yuda around 25 kp ~ 27 kp, Kawajiri around 29 kp, Kurosawa around 36 kp, and Sannai around 28 kp ~ 40 kp. The slow-down in and around these tunnels is considered to be caused by lighting contrast and oppressive feeling when driving through the tunnels, and conforms to the findings to date that tunnels could become as bottlenecks of traffic flow.

Further, vehicle speed increases substantially on the auxiliary lanes due to frequent overtaking, but decreases quickly at the end of the auxiliary lanes around 23 kp and 33.5 kp as the fast-moving vehicles catch up with and cannot pass slow-moving vehicles further ahead. The sudden deceleration at high traffic flow levels is probably caused by flow disturbances due to forced merging as they travel downstream of the end of auxiliary lanes.

Overall, aside from the sudden speed drop immediately downstream of the end of auxiliary lanes, as well as repeated local slow-downs due to longitudinal gradients and tunnels as mentioned above, the vehicle speed tends to decline gradually over the entire length of this section. This tendency is more pronounced at higher traffic flow levels.

In the basic TWTL (one lane on each side) sections, the travel speed tends to be higher when the traffic flow is lower (200 ~ 400 pcu/h) than when it is higher (800 pcu/h or higher). However, the tendency is reversed in sections with auxiliary lanes (around 21 kp ~ 23 kp and 32 kp ~ 33 kp). This is likely because more vehicles use an auxiliary lane for overtaking when the traffic flow is 600 pcu/h or higher than when it is lower. Increased speed on auxiliary lanes, however, does not last very long, and vehicles start to slow-down at and immediately downstream of the merge taper. Speed tends to pick up again further downstream.

The slow-down mechanism at and immediately downstream of the merge taper can be explained as follows: when the flow rate is high, vehicles on an auxiliary passing lane try to merge forcefully into vehicles on the through lane at the end of the auxiliary lane, forcing the vehicles to slow-down to adjust to suddenly reduced inter-vehicular space. When a sufficient inter-vehicular space is regained, the speed returns.

One of the indices of the effectiveness of adding an auxiliary lane is the distance over which the travel speed is maintained, which is the distance from the end of the auxiliary lane to the point at which vehicle speed drops to the same level as that upstream of the auxiliary lane. Fig. 2 shows that the distance is about 1.0 to 1.5 km, which is much shorter than 2.7 km indicated in Highway capacity Manual (HCM) (2).

It is also possible that other factors have compounding effects on the slow-down at and immediately downstream of merge tapers in addition to the above-mentioned longitudinal geometry, tunnels, etc.

3.3. Identifying factors causing slow-down on TWTL expressways

The previous section analysed the slow-down phenomena on two representative expressways based on spatial speed variation data captured by ETC 2.0 probe data. This section analyses the causes of slow-down on 78 TWTL expressways (sections) in Japan.

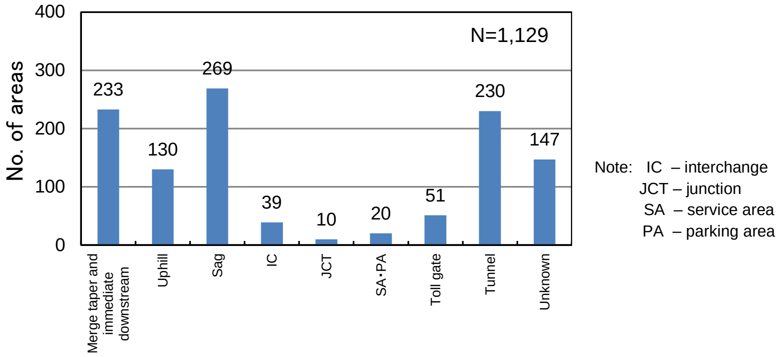
Similar to the analysis result of the previous section, slow-down areas become more apparent at higher traffic flow levels. However, as not all expressways in Japan have high traffic volume, drawing speed profiles only at high flow levels will result in an insufficient sample size in many sections.

In this section, therefore, speed profiles of target sections are drawn based on ETC 2.0 probe data of vehicles that travelled the sections when the traffic flow was at the same level as their respective average peak hour traffic volumes.

As discussed in the previous section, vehicles on TWTL expressways tend to travel faster on auxiliary lanes and slow down immediately downstream of the end of auxiliary lanes, at sags, tunnels, etc. However, as slow-down patterns vary depending on the location, it is necessary to define the term “slow-down” that can be applied to all TWTL expressways. In this study, a slow-down area is defined as a location where the speed difference between the point at which deceleration begins and the point at which acceleration begins is 5 km/h or greater to examine the factors causing slow-down by referring to road structure drawings, road alignment drawings, digital road maps, etc.

According to the above definition, there are 986 slow-down areas on 78 TWTL expressways in Japan. As a result of analysing the slow-down at each area, we found 1,129 factors causing slow-down as summarized in Fig. 3. There are more factors than the number of slow-down areas because some areas have more than a single factor. Of the 1,129 factors, sags account for 269, followed by merge tapers and immediately downstream accounting for 233 and tunnels for 230. There are also 147 areas where the cause of slow-down is unknown.

Figure 3: No. of slow-down areas by cause



4. Results

Based on the different causes of slow-down as shown in Fig. 3 change in longitudinal gradient, slow-down locations, distance between the slow-down location and the end of the auxiliary lane, etc., in sags, merge tapers and immediately downstream of merge tapers, and tunnels are analysed.

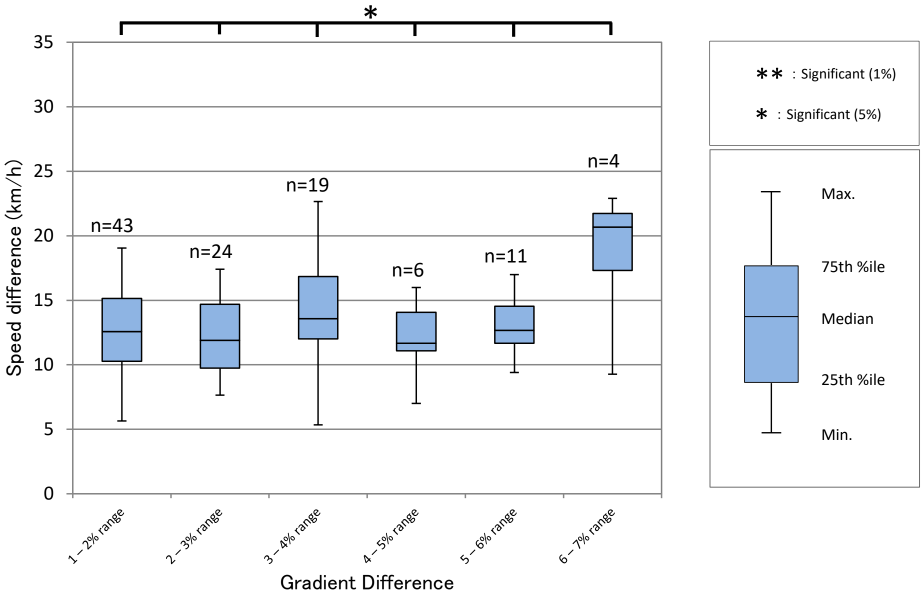
4.1. Analysis of Slow-down in Sags

Of the 269 slow-down areas in sags shown in Fig. 3, 53 areas have data with a sufficient sample size at the 600 ~ 800 pcu/h level. Slow-down behaviour of the 53 areas is analysed from three viewpoints: a) gradient difference in a sag, b) slope geometry (downhill to uphill, steep downhill to moderate downhill, moderate uphill to steep uphill), and c) distance from the end of auxiliary passing lane to sag.

4.1.1. Gradient difference in sag

Differences in gradient and vehicle speed in and around sags in the 53 areas are aggregated and summarized in Fig. 4, where the gradient difference between 1% downhill and 2% uphill slopes is calculated as 3%. While 6 ~ 7% gradient difference shows the greatest slow-down, greater gradient difference does not necessarily translate to greater slow-down.

Figure 4: Slow-down due to sag gradient difference

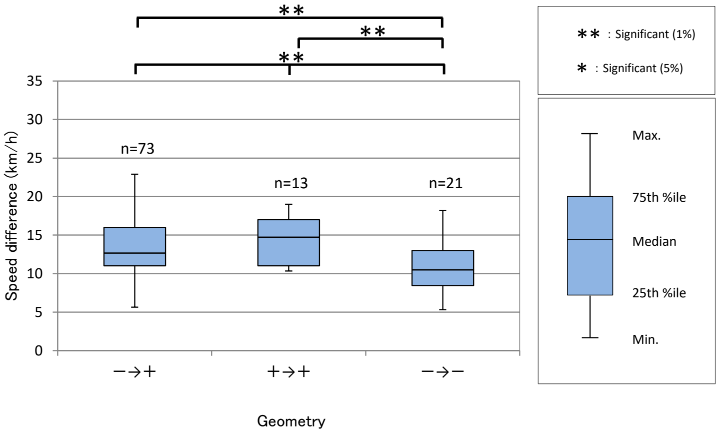


4.1.2. *Slope geometry*

Fig. 5 summarizes the average speed in and around sags with different slope geometries: downhill to uphill (- to +), steep downhill to moderate downhill (- to -), and moderate uphill to steep uphill (+ to +).

Among the three different types of sags, the biggest slow-down occurs in moderate uphill to steep uphill (+ to +) sags, as steep uphill contributes to deceleration, followed by downhill to uphill (- to +) slopes. Slow-down is not as apparent in steep downhill to moderate downhill (- to -) sags, as it is relatively easy for drivers, upon noticing slow-down due to a sag, to pick up speed on moderate downhill slopes.

Figure 5: Slow-down due to sag geometry

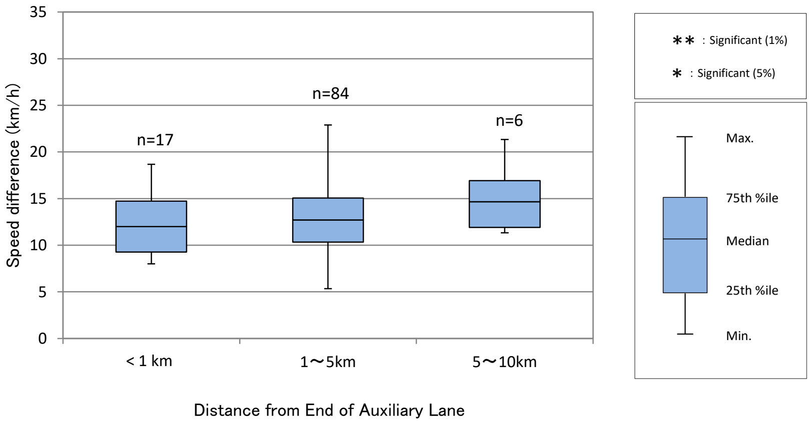


4.1.3. *Distance from end of auxiliary passing lane*

The 53 areas are divided into three groups according to the distance between the sag and the end of the auxiliary passing lane: less than 1 km, 1 ~ 5 km, and 5 ~ 10 km. The average speed differences for the three groups are summarized in Fig. 6.

Contrary to Subsections 4.1.1 and 4.1.2, there is no statistically significant difference among the groups though there is a slight tendency that the longer the distance, the greater the slow-down, which suggests the occurrence of small speed disturbances within a platoon in the sag area, causing amplification and propagation of deceleration waves upstream.

Figure 6: Slow-down due to distance from the end of auxiliary passing lane



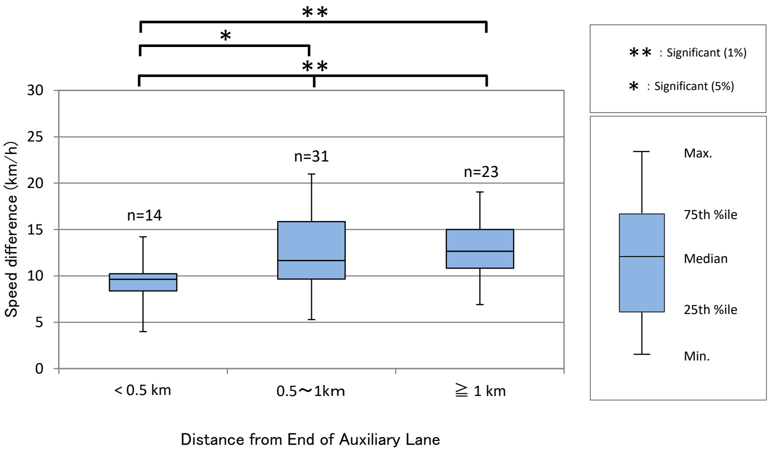
4.2. Analysis of slow-down at and immediately downstream of merge tapers

Of the 233 slow-down areas at and immediate downstream of merge tapers, 68 areas have data with a sufficient sample size at 600 ~ 800 pcu/h level. Slow-down patterns of the 68 areas are analysed from the viewpoints of: a) distance from the end of the auxiliary lane, and b) length of the auxiliary lane.

4.2.1. Distance from end of auxiliary passing lane

The average speed difference between the end of the auxiliary passing lane and the point where vehicle speed drops to the lowest level in each of the 68 areas is sorted out according to the distance between the two points and is summarized in Fig. 7, in which the distance is divided into three groups: less than 0.5 km, 0.5 ~ 1.0 km, and 1.0 km or longer. The figure indicates that the greater the distance from the end of the auxiliary lane, the greater the slow-down.

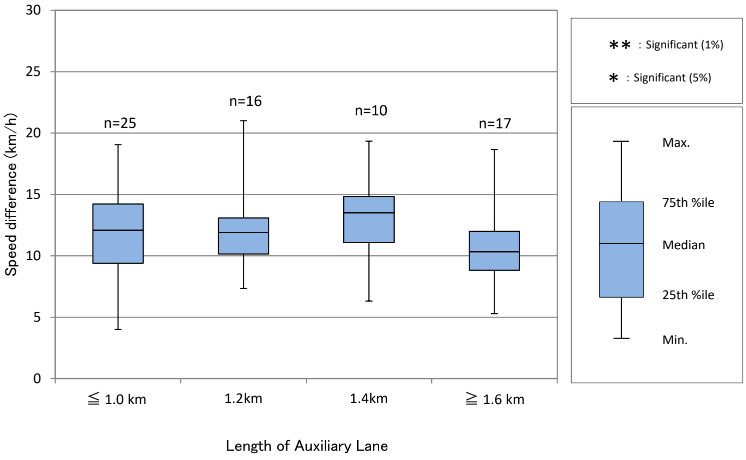
Figure 7: Slow-down due to distance from the end of auxiliary passing lane



4.2.2. Length of auxiliary passing lane

The average speed difference between the end of the auxiliary passing lane and the point where vehicle speed drops to the lowest level in each of the 68 areas is sorted out according to the length of the auxiliary lane and summarized in Fig. 8, in which the auxiliary lane length is divided into the following groups: less than 1.0 km, 1.0 ~ 1.2 km, 1.2 ~ 1.4 km, 1.4 ~ 1.6 km, and 1.6 km or longer. As shown in the figure, the length of the auxiliary lane has little influence on slow-down.

Figure 8: Slow-down due to length of auxiliary passing lane



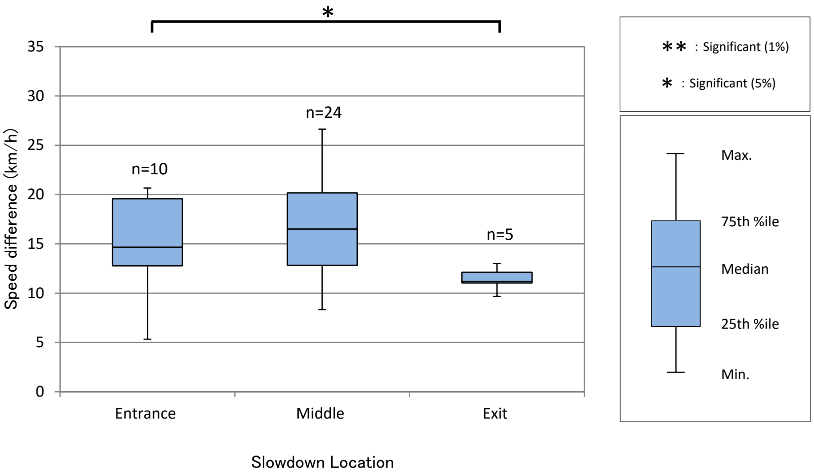
4.3. Analysis of slow-down in tunnel sections

Of the 230 slow-down areas in tunnel sections shown in Fig. 3, 39 areas have data with a sufficient sample size at 600 ~ 800 pcu/h level. Slow-down patterns in the 39 tunnel areas are analysed from the standpoints of: a) location of slow-down within a tunnel, b) longitudinal gradient (sag, crest, uphill, downhill) of the location of slow-down, and c) distance from the end of the auxiliary lane.

4.3.1. Location of slow-down within a tunnel

The average speed difference between the end of the auxiliary lane and the point where vehicle speed drops to the lowest level in each of the 39 tunnel areas is aggregated and summarized in Fig. 9. The slow-down locations are divided into three groups of entrance, inside, and exit, where entrance and exit are defined as the areas within 200 m from the tunnel entrance and exit, respectively. The figure indicates that slow-down is greater inside the tunnel than in the entrance/exit areas, which may be due to the longitudinal gradient inside the tunnel.

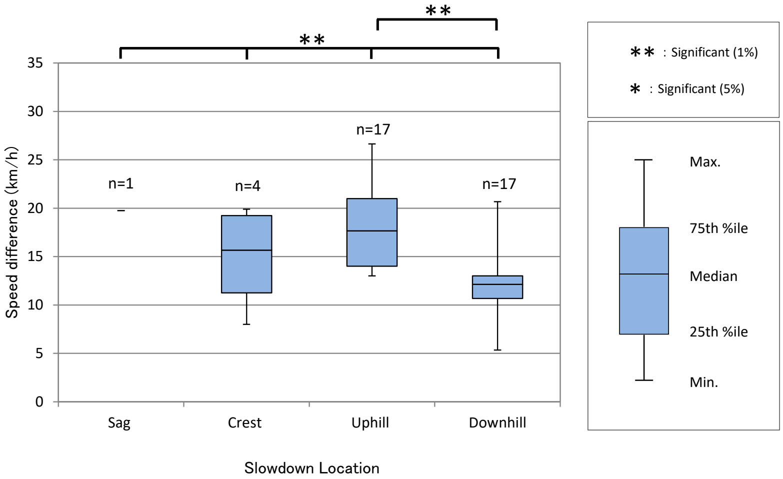
Figure 9: Slow-down due to location within tunnels



4.3.2. Road structure of slow-down location inside a tunnel

The average speed difference between the end of the auxiliary lane and the point inside a tunnel at which the speed drops to the lowest level in each of the 39 tunnel areas is sorted out according to the longitudinal gradient (sag, crest, uphill, and downhill) and is summarized in Fig. 10. As shown in the figure, uphill causes the largest slow-down, which is likely aggravated by lighting contrast and narrow shoulder widths inside a tunnel.

Figure 10: Slow-down due to road structure inside tunnels

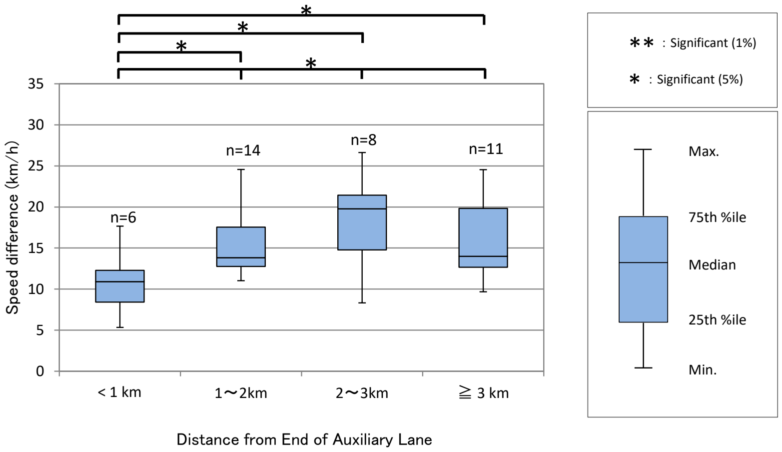


4.3.3. Distance from end of auxiliary passing lane

The average speed difference between the end of the auxiliary passing lane and the lowest speed point inside the tunnel in each of the 39 areas is sorted out according to the distance between the two points and is summarized in Fig. 11, in which the distance is divided into four groups: less than 1.0 km, 1.0 ~ 2.0 km, 2.0 ~ 3.0 km, and 3.0 km or longer.

The figure indicates that the longer the distance from the end of the auxiliary lane, the greater the slow-down, except that slow-down is greater when the distance is 2.0 ~ 3.0 km than when it is 3.0 km or longer. It is highly possible that the areas situated 3.0 km or longer from the end of the auxiliary lane are affected not only by the tunnel structure but also by temporary speed recovery due to downhill slopes, etc.

Figure 11: Slow-down due to distance from auxiliary lane end



5. Conclusions and future work

This study confirmed the following results with respect to traffic flow and operational performance on TWTL expressways. The results can be used to identify the location of decline in and help improve operational performance and to review installation guidelines of passing lanes on TWTL expressways.

5.1. Local slow-downs due to longitudinal gradient, etc.

Slow-down tends to occur in confined spots due to sag and other longitudinal gradient, as well as tunnels and other road structures. While this type of slow-down is also seen on roads with multi-lane sections, it is more pronounced on TWTL expressways even at low traffic flow levels. This is because the average capacity of TWTL sections of 1,000 ~ 1,300 pcu/h is much lower than that of multi-lane sections and also because overtaking is prohibited except in sections with an auxiliary passing lane, making it difficult for a platoon to dissipate easily once it is formed (10, 11).

5.2. Slow-down tendency at and immediately downstream of merge tapers

Vehicles tend to travel faster in TWTL sections when the traffic flow is low, as well as on auxiliary passing lanes when the traffic flow is high because more vehicles tend to use the auxiliary passing lanes to accelerate for overtaking. In addition, vehicles tend to slow-down more at and immediately downstream of a merge taper when the traffic flow is higher than when it is lower. The conceivable reason is that as overtaking vehicles merge within a platoon or between platoons on the through lane at the end of an auxiliary lane, vehicles travelling immediately downstream of the merge taper have to adjust quickly to a suddenly reduced inter-vehicular space due to high traffic flow.

5.3. Future work

This study analysed the traffic flow conditions of TWTL expressways using ETC 2.0 probe data. The results show that vehicle speed tends to decrease gradually over the lengths of such expressways except in downhill sections, with local slow-downs occurring at and immediately downstream of merge tapers of auxiliary passing lanes, as well as speed drops in confined areas due to sags and uphill gradients. The results also show that these slow-down tendencies are more pronounced at higher traffic flow levels.

As higher traffic volumes lead to faster vehicle speed on auxiliary passing lanes and greater slow-down at the merge taper, it will be necessary to examine the possibility of extending auxiliary passing lanes and to determine the appropriate locations of their end points according to the traffic flow volume.

In addition, it will be necessary to predict the speed profiles of TWTL sections downstream of auxiliary lanes in order to understand their effects on preventing slow-down. While such prediction is possible by microscopic traffic simulation, it is also possible to use the speed profiles obtained in this study to create a simple prediction model for estimating a speed profile after installing an auxiliary lane, in which case, the development of an accurate prediction model remains a challenge to be overcome in the future.

6. References

1. MLIT of Japan website: http://www.mlit.go.jp/policy/shingikai/road01_sg_000250.html. (Accessed 2 September 2016).
2. Transportation Research Board. (2010). Highway Capacity Manual. Fifth Edition, TRB, National Research Council, Washington, DC.

3. Oregon Department of Transportation. (2014). Modeling Follower Density on Two-Lane Rural Highways.
4. Fitzpatrick, K. and Collins, J. M. (2000). Speed-profile model for two-lane rural highways. Transportation Research Record: Journal of the Transportation Research Board, 1737, pp. 42–49.
5. Fitzpatrick, K., Miaou, S., Brewer, M., Carlson, P., and Wooldridge, M. (2005). Exploration of the Relationships between Operating Speed and Roadway Features on Tangent Sections. ASCE Journal of Transportation Engineering, Volume 131, Issue 4.
6. National Academies of Sciences, Engineering, and Medicine. (2018). Improved Analysis of Two-Lane Highway Capacity and Operational Performance. Washington, DC: The National Academies Press. https://doi.org/10.17226/25179.
7. Al-Kaisy, A., Jafari, A., Washburn, S., Luttinen, T., and Dowling, R. (2018). Traffic Operations on Rural Two-Lane Highways: a Review on Performance Measures and Indicators. Presented at 97th Annual Meeting of the Transportation Research Board, Washington D.C.
8. Moreno, A.T., Llorca, C., and García, A. (2016). Operational Impact of Horizontal and Vertical Alignment of Two-Lane Highways. Transportation Research Procedia, Vol. 15, pp. 319–330.
9. Austroads. (2019). Passing Lanes – Safety and Performance. Research Report AP-R596-19.
10. Yoshikawa, R., Nagahama, K., Xing, J., Yoshii, T., and Kitamura, R. (2005). A Study on Bottleneck Capacity on Divided Two-lane Expressways. Infrastructure Planning Review, No.22.
11. Yoshikawa, R., Shiomi, Y., Yoshii, T., and Kitamura, R. (2008). A Study on Bottleneck Capacity on Divided Two-lane Expressways. Traffic Engineering, Vol. 43, No. 5, pp. 48-58.
12. Shiomi, Y., Yoshii, T., and Kitamura, R., and Yoshikawa, R. (2006). Bottleneck Capacity Prediction Simulation for Two-way Two-lane section of Tokai-Hokuriku Expressway. In Proceedings 36th JSTE Annual Conference, pp. 45-48.
13. Utsumi, Y., Hamaoka, H., and Nakamura, H. (2011). Study on the Estimation of Speed-Flow Relationships for Divided Two-Way Two-Lane Expressway Sections. Journal of Japan Society of Civil Engineers D3, Vol. 67, No. 3, pp. 261-269.
14. Catbagan, J. and Nakamura, H. (2006). Evaluation of Performance Measures for Two-Lane Expressways in Japan. Transportation Research Record: Journal of the Transportation Research Board, 1988, TRB, National Research Council, Washington, D.C., pp. 111-118.
15. Nakamura, H., Kobayashi, M., and Catbagan, J. (2011) A Study on Implementation Policy of Auxiliary Passing Lane on Two-way Two-lane Highways Considering Follower Density. Journal of Japan Society of Civil Engineers D3, Vol. 67, No. 3, pp. 270-282.
16. Kanoshima, H., Suzuki, K., Nonaka, Y., and Makino, H. (2015). Application of ETC 2.0 Probe Data to Bottleneck Analysis on Expressways. In Proceedings 35th JSTE Annual Conference, pp. 215-221.
17. Narushima, S., Murashige, Y., Xing, J., Doi, M., and Suda, M. (2015). A Study on Utilizing ETC 2.0 Probe Data for Detection of Visibility Obstruction, In Proceedings Infrastructure Planning, Vol.51.
18. Ebara, Y., Ito, T., and Narita, N. (2016). Extraction of Potential Black Spot in the Expressway of Hokkaido Using ETC 2.0 Probe Data. In Proceedings 36th JSTE Annual Conference, pp. 223-227.

19. Narushima, S., Kasai, M., Xing, J., Goto, H., and Tsuji, M. (2017). Analysis of Vehicle Speeds on Two-way Two-lane Expressways with ETC 2.0 Data. Journal of Japan Society of Traffic Engineers, Vol. 3, No. 2, pp. A_125-A_134.
20. Kasai, M., Xing, J., Narushima, S., Goto, H., and Tsuji, M. (2017). A Discussion on Measure of Effectiveness of Two-way Two-lane Expressways. Journal of Japan Society of Traffic Engineers, Vol. 3, No. 2, pp. A_135-A_144.