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DRIVING STRESS OF DRIVERS ON NARROWED LANE AND HARD SHOULDER OF MOTORWAYS

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Abstract

In order to reduce congestion on a section of motorway, a new type of hard shoulder running (HSR) scheme or a tentative 3-lane operation scheme had been in use since October 21, 2011 for the first time in Japan. It is different from those that have been applied in other countries in that it operates all day long, while the latter operates only during peak periods. As a result, traffic congestion was reduced significantly. Nevertheless, before the operation, road operator was slightly worried about the impact of narrowed widths of lanes and hard shoulder on drivers' stress while driving. The paper evaluates the impact of narrowed lanes and hard shoulder on young and senior drivers' stress while driving during the operation of the tentative 3-lane scheme by comparing it among normal 3-lane, 2-lane and tentative 3-lane sections.

Keywords

Hard Shoulder Running, Traffic Congestion, Motorway, Driving Stress, Traffic Safety

1. Introduction

In order to reduce congestion on a section of motorway, a hard shoulder running (HSR) scheme or a tentative 3-lane operation scheme was adopted for the first time in Japan from October 21, 2011. The scheme converts the original dual 2-lane motorway to a tentative dual 3-lane motorway by effectively using hard shoulder and narrowing existing lanes as shown in Figure 1 and Photo 1. The scheme is different from those that have been applied in other countries in that it operates all day long, as the latter operates only during peak periods. As a result, traffic congestion was reduced significantly (Sato et al., 2012, Maeda et al., 2012, Konda et al., 2013). Nevertheless, before the tentative 3-lane operation, road operator was slightly worried about the impact of narrowed lane widths and the hard shoulder on drivers' stress while driving. High driving stress can cause drivers early fatigue, which may result in an accident (Howard et al., 1994). Therefore, detecting and monitoring driver state such as driving stress, driver fatigue and drowsiness is an important issue in traffic safety and intelligent transport systems (ITS) that can help reduce potential traffic accidents (Jung et al., 2014, Chen et al. 2017). The objective of this paper is to evaluate the impact of narrowed lane widths and hard shoulder on drivers' stress while driving during the operation of the scheme by comparing the driving stress among normal 3-lane, 2-lane and tentative 3-lane sections.

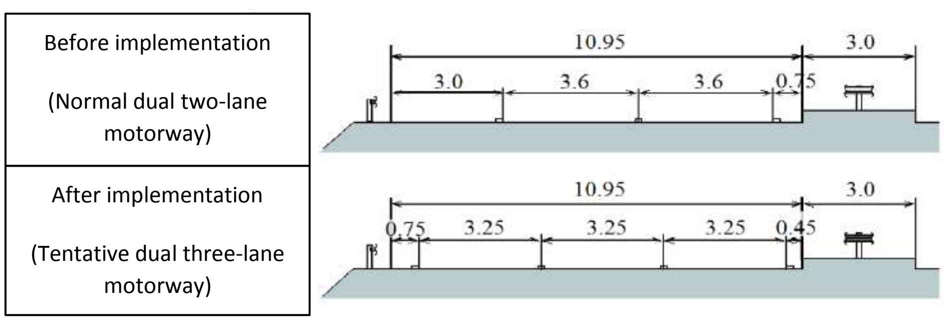


Figure 1: *Cross-section of tentative 3-lane carriageway*

a) Before operation b) After operation

Photo 1: *Snapshots before and after operation of tentative 3-lane scheme*

2. Outline of the Study

2.1 Driving Experimental Section

The driving experiment was carried out in two sections on Tomei Motorway: a section between Toyoda and Toyokawa ("Toyoda section") that consists of the tentative 3-lane section from Toyoda Junction to Otowagamadgori and the remaining normal 2-lane sections, and a normal 3-lane section between Yokohama-Aoba and Hadano-Nakai ("Yokohama section") as shown in Figure 2. Consequently, the driving experimental section comprises three sections, that is, the tentative 3-lane section, and the normal 2-lane and 3-lane sections. The last two sections were used for comparison with the tentative 3-lane section.

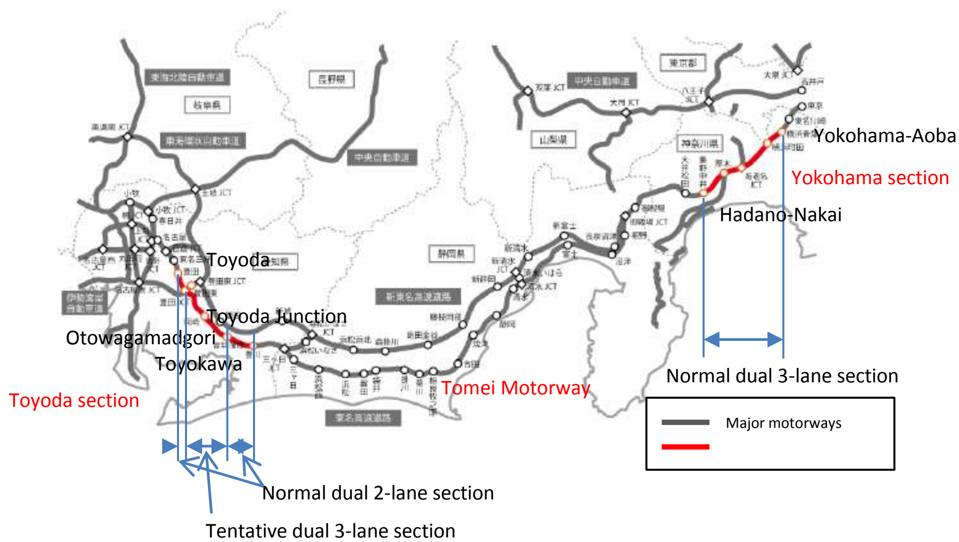


Figure 2: *Location map of driving experimental section*

2.2 Driving Experiment

The driving experiment participants consisted of 12 senior drivers (aged 60 or older) and 20 younger drivers. Each participant was requested to drive the three sections.

They wore various measuring devices while driving and made two round trips in each section. For the 3-lane sections, drivers basically used outer lane during the first round trip and middle lane during the second round trip except for overtaking. For the 2-lane sections, drivers basically only used outer lane for two round trips. However, participants were allowed to overtake a vehicle in front of them, because driving behind a slow car may cause extra stress. Drivers decided by themselves whether they should overtake such a vehicle or not.

2.3 Measurement Items and Method

Items shown in Table 1 were measured in the driving experiment. The data collected includes driver's attributes, road alignment, traffic condition, driving environment around test cars, vehicle behavior such as speed, acceleration and steering wheel operation, driver's mental and physical conditions such as electrocardiogram, eye movement and Flicker value. The electrocardiogram was measured through vital sensors attached to the test drivers' bodies to produce some indices such as heart rate, HF and HF/LF ratio, which are usually used to evaluate driver's stress and sense of tenseness while driving. Eye movement was measured by an eye mark camera to obtain point of regard, stationary time, number of saccades and heat map. The Flicker value was measured by a Flicker measuring device to check the driver's fatigue status. In addition, a drive recorder was used to collect GPS data (time, latitude/longitude, speed and acceleration on an XYZ axis) and the front image and driver's face image for each second. Test drivers were also asked to finish a VAS (visual analog scale) questionnaire survey after each drive to report their feelings of tenseness and fatigue.

Table 1: *List of data collected in the study*

Item		Data to be collected	Data collection method
Driver's Attribute		·Personal attribute (age, driving experience, etc.) ·Driving feature (HQL style check sheet)	·Questionnaire
Factors of Mental and Physical Impacts	Road condition	·Road structure ·Horizontal alignment, vertical alignment, motorway cross-section (width) ·Road adjuncts (road signs, atc.)	·Route map ·Drawings for management ·Sign management file, drive recorder
	Traffic condition	·Traffic volume, speed (traffic volume and speed level in experiment) ·Occurrence of congestion and accidents (selection of singular events)	·Traffic counter data ·Control event data
	Driving environment	·Surrounding vehicles ·Accidents, broken-down vehicles ·Weather and darkness/brightness	·Drive recorder
	Vehicle behavior	·Changes in speed and acceleration ·Steering wheel operation (lane change)	·Drive recorder
Mental and Physical Conditions		·Electrocardiogram (HR, HF, LF/HF) ·Eye movement (point of regard, stationary time, number of saccades, heat map) ·Flicker value (sense of fatigue) ·Face image	·Vital sensor ·Eyemark camera ·Flicker measuring device ·Car-mounted video system
		·Sense of fatigue, sense of tenseness	·VAS (visual analog scale) questionnaire ·Voice recorder

2.4 Traffic Flow Diagram

Figure 3 shows a comparison of traffic flow diagrams of each lane in both normal and tentative 3-lane sections. It is seen from the figure that the both diagrams are similar to a large extent. Though speed limit in tentative 3-lane section was set at 60 km/h due to lane width constraint, actual speed is much higher than the speed limit and is almost the same as that of normal 3-lane section.

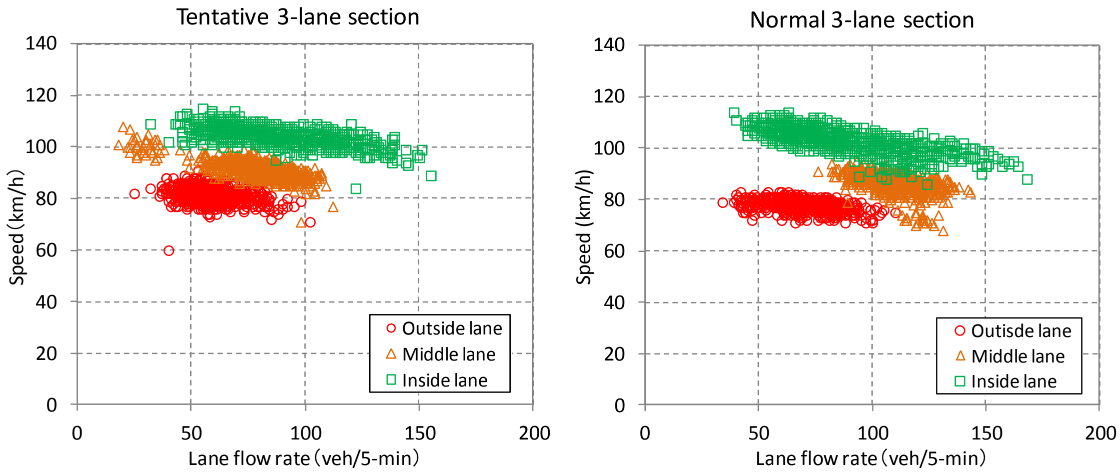


Figure 3: *Traffic flow diagrams of normal and tentative 3-lane sections*

3. Evaluation Indicators of Driving Stress

3.1 Evaluation Indicators of Driving Stress

A number of existing studies have made clear that heart rate response, directly and indirectly, connecting with various life-action behaviors including driving tasks, is deeply related to autonomic nervous system activity (e.g. Kato et al., 2006). Kawai et al. (2003) shows that the ratio of low frequency to high frequency (LF/HF ratio), which is calculated from the time series of heartbeat rate variability, reflects the activity of the sympathetic nervous system (a part of the autonomic nervous system controlling the functioning of the circulatory system and internal organs). According to a recent study conducted by Jung et al. (2014), the LF/HF ratio can also be used to identify and monitor driver fatigue and drowsiness on steering wheel.

In past studies, the LF/HF ratio of participants of young drivers and senior drivers in the experimental round trip drive from Oi-Matsuda to Numazu via Gotenba on Tomei Motorway was compared. It was used as one of several stress evaluation indicators to classify the degree of stress or tenseness as follows, which had also been utilized in previous studies (Takahashi et al., 2013).

a) LF/HF 10 or below: non-tense sympathetic nervous system level;
b) LF/HF 11 to 29: slightly tense driving level;
c) LF/HF 30 or higher: highly tense driving level.

Similarly, the LF/HF ratio is also taken in this study as an indicator to evaluate drivers' stress levels while driving after confirming its validity of the classification of the degree of stress with the LF/HF ratio.

3.2 Confirmation of Validity of LF/HF Ratio as a Stress Evaluation Indicator

In the study, we use the LF/HF ratio data of all participants obtained in the test drives and video data gathered from the drive recorder to examine the validity of the classification of degree of stress with the LF/HF ratio.

3.2.1 Boundary between Non-tense and Slightly Tense Conditions

Figure 4 shows the LF/HF ratio frequency distribution while driving based on the LF/HF ratio data of every two seconds of the entire drive of all participants in the Yokohama and Toyoda sections. The results indicate that LF/HF=10 is around the 90 percentile value of the distribution. This means nearly 90% of the driving time is in the state of a non-tense condition, which is in accordance with our intuition as a driver.

In order to figure out what kind of driving behavior may cause the LF/HF ratio to increase, all the data for which the LF/HF ratio exceeds 10 were selected from the time immediately before the LF/HF ratio exceeded 10 to the time when it became lower than 10 in the Yokohama and Toyoda sections for all participants. However, it is counted as one event when the duration from the time when the LF/HF ratio became lower than 10 to the time when it exceeded 10 again is short enough (for example, less than 30 seconds).

As an example, Figure 5 plots a time series of the LF/HF ratio of one driver while driving. These cases were analyzed to identify the driving behaviors to check if they would be in a tense driving condition while driving from traffic engineer's viewpoint. From the analysis results, the driving behaviors that tend to cause high stress were identified and classified as follows.

• They were passed by a large vehicle on the right side while passing a large vehicle on the left side. (①)

• They were passed by a small vehicle on the right side while passing a large vehicle on the left side. (⑤)

They passed a large vehicle on the left side. (④, ⑦)

• They passed a small vehicle on the left side. (②)

• They overtook a large vehicle from the right side. (③, ⑨, ⑩, ⑫)

• No particular event (⑥, ⑧, ⑪)

It is found that events related with passing, overtaking, and being passed or overtaken were more likely to cause the LF/HF ratio to exceed 10, and the ratio would not exceed 10 in other cases when participants were not passed or overtaken by the surrounding vehicles and when they did not pass or overtake the surrounding vehicles. Consequently, the boundary between slightly tense and non-tense conditions being LF/HF=10 is validated. In addition, the LF/HF ratio increased even with no surrounding vehicles when the sunshine condition changed significantly from shadow to sunlight or when they reacted to the vibration that occurred when they passed over joints.

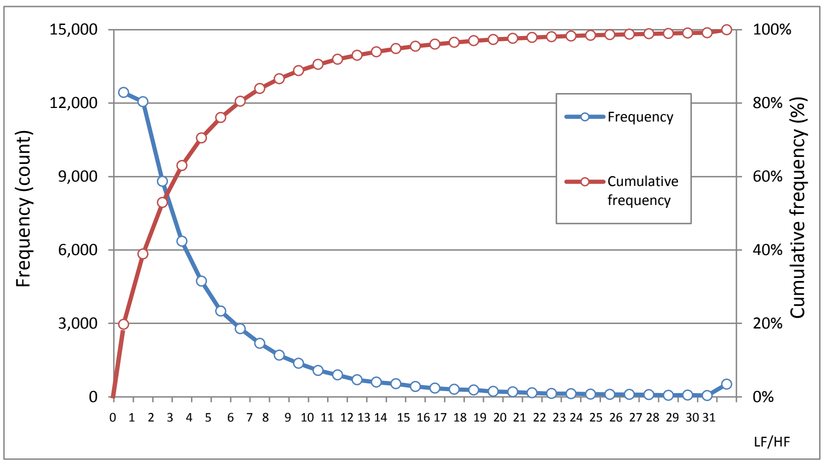


Figure 4: *LF/HF ratio frequency distribution during driving in the three sections*

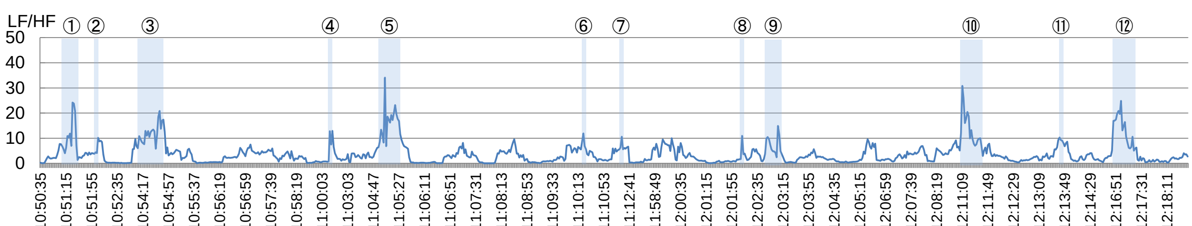
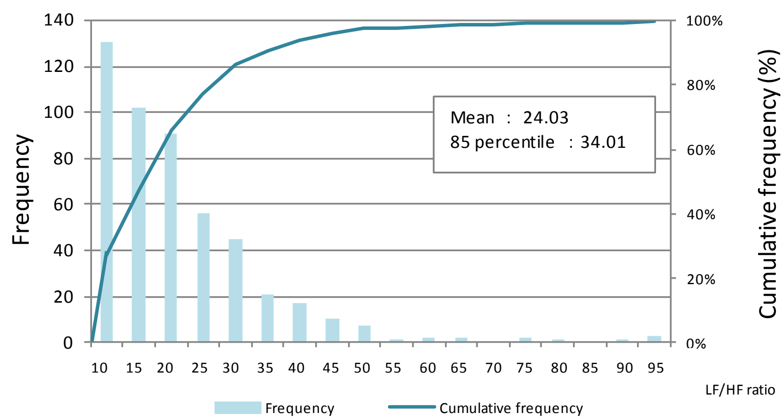


Figure 5: *Time-series measurement result while driving: an example in Yokohama section*

3.2.2 Boundary between Slightly Tense and Highly Tense Conditions

Regarding the events where the LF/HF ratio exceeded 10 in both the Yokohama and Toyoda sections, the waveform peak value (maximum value) of the LF/HF ratio was taken to calculate their mean value and 85 percentile value. The distribution of the peak LF/HF ratio is shown in Figure 6.

The mean value of the peak LF/HF ratio distribution is 24 and the 85 percentile value 34. This is mostly consistent with the LF/HF ratio boundary of 30 while driving, which was used to define a highly tense condition in motorway driving environment after examining the data obtained from the test drives between Oi-Matsuda and Numazu via Gotenba on Tomei Motorway in the past studies by Takahashi et al. (2013). Consequently, LF/HF=30 is validated as the threshold of judging the highly tense driving condition.



Sample size: N=492 (normal 3-lane section:283; tentative 3-lane section:110;
normal 2-lane section:99)
Events confirmed with no particular condition from images of driver recorder were excluded.

Figure 6: *Peak LF/HF ratio distribution while driving in tense conditions of normal and tentative 3-lane sections*

4. Evaluation of Driving Stress Caused by Narrowed Lane and Hard Shoulder

Here in the study, the impact caused by narrowed lane and hard shoulder was evaluated by comparing driving stress measured from three different sections of normal 2-lane section and 3-lane section and tentative 3-lane section. Twenty young and 12 senior drivers were asked to drive in the same three different sections. Figure 7 shows the LF/HF ratio for three different sections for both young and senior drivers tested. It seems that there is no distinct difference among the three sections and between age groups. According to the above categorization of driving stress, drivers did not feel strong stress more than 95% of the driving time, but might feel slightly stressful only a fraction of the driving time. Strong stress was not measured in our driving tests.

Figure 8 shows a comparison of the LF/HF ratio in three different sections by lane (outside lane & middle lane) and time period of day (daytime/nighttime). Looking at the LF/HF ratio in tentative 3-lane section, there seems to be no difference between outside lane and middle lane in daytime. In the nighttime, however, middle lane seems to yield a slightly higher stress than outside lane. This higher stress probably comes from the narrowed lane width, high speed in middle lane and even higher speed in inside lane, and high percentage of heavy vehicles. Only the upper quartile fell into a slightly tense state. Nevertheless, there seems to be no difference between the normal 3-lane section and the tentative 3-lane section.

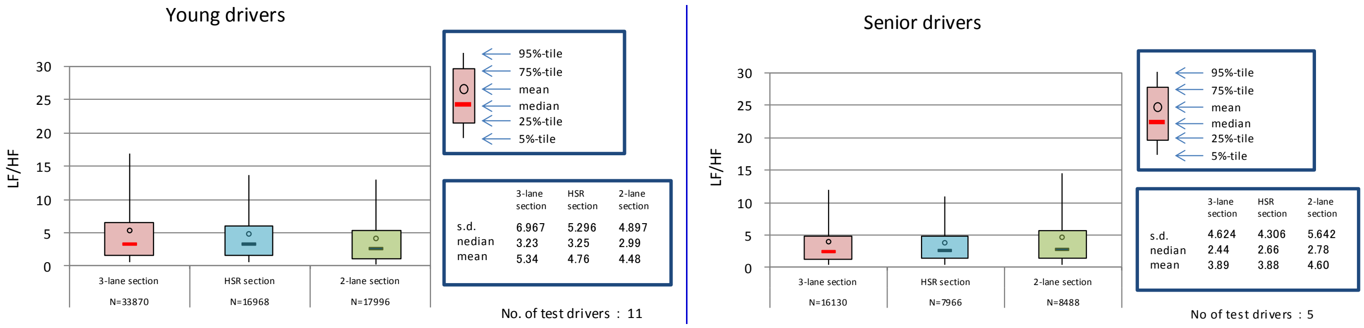
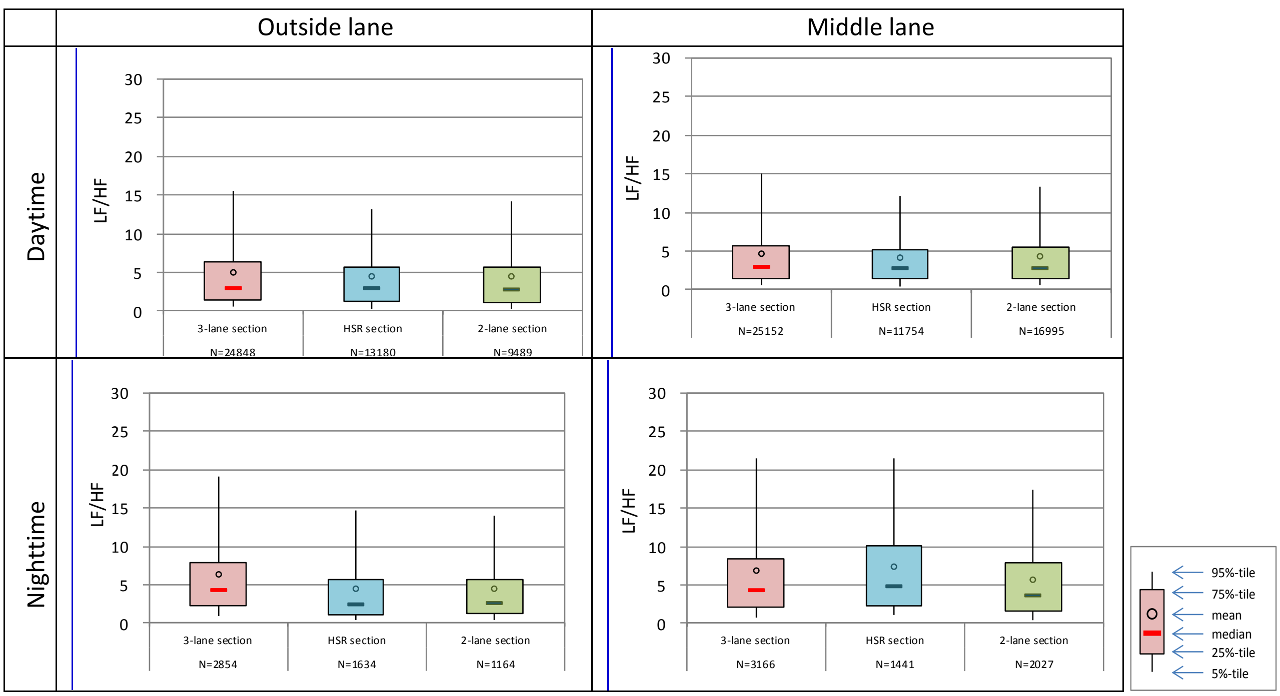


Figure 7: *LF/HF ratio in different sections by driver age*



Note: Middle lane in 2-lane section is the same as Outside lane.

Figure 8: *LF/HF ratio in different sections by lane and time of day*

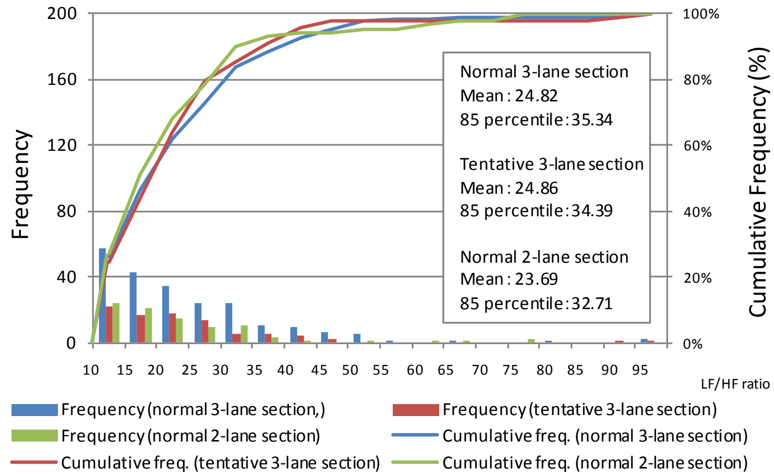


Figure 9: *Comparison of LF/HF ratio distributions while driving in tense conditions of different cross-sections*

Furthermore, the LF/HF ratio in the occurrence of driving behaviors accompanied by tense conditions as aforementioned was used to evaluate the impact of different motorway cross-sections on driving stress. Figure 9 shows a comparison of the LF/HF ratio frequency distributions in tense conditions of different cross-sections. It can be seen from the figure that the cumulative distribution of the LF/HF ratio is almost the same for the three different cross-sections. Driver behaviors in highly tense driving condition with the ratio of LF/HF ratio exceeding the threshold of 30 account for 16% in the normal 3-lane section of the Yokohama section and 15% in the tentative 3-lane section of the Toyoda section. This means that the level of stress affecting mental and physical conditions by three different cross-sections is almost the same. In general, driving behaviors in slightly tense condition account for more than 80%, and driving behaviors in highly tense condition account for only less than 20%.

Therefore, it is seen from the comparison that there's no evidence to show more driving stress for both young and senior drivers on the tentative 3-lane section with narrowed lane and hard shoulder widths compared with the normal 2-lane and 3-lane sections.

5. Conclusions and Future Issues

In this study, we first examined the criteria of driver stress evaluation by identifying incidences of driving behaviors that affect stress changes, and then evaluated the impact on driving stress of three different motorway cross-sections including a tentative dual 3-lane section with narrowed lanes and hard shoulder based on actual test drive data of the same young and senior drivers.

It is found from the study that the LF/HF ratio can be used as an index to assess driving stress levels, and the thresholds of 10 and 30 are appropriate to define slightly and highly tense conditions. No tenseness will be observed most of the time while driving with the LF/HF ratio of equal to or less than 10. The driving stress level increases significantly with the LF/HF ratio exceeding 10, particularly when drivers drive side by side with a large vehicle in such situations relating with the traffic events of passing or overtaking, and being passed or overtaken. Among the tense driving state, driving behaviors in slightly tense condition ($10 < LF/HF < 30$) account for more than 80%, while driving behaviors in highly tense condition ($LF/HF \geq 30$) account for only less than 20%.

Comparing the distribution of the LF/HF ratio of driving behaviors in tense conditions of the tentative 3-lane section with that of the normal 2-lane and 3-lane sections, it is found that there is no significant difference between the normal 3-lane section in the Yokohama section and the tentative 3-lane section with narrowed lanes and the hard shoulder in the Toyoda section. Accordingly, it is fair to conclude that the stress level affecting mental and physical conditions by narrowed lanes and the hard shoulder is almost the same. Vehicle speeds in the three different cross-sections are similar although speed limit in the tentative 3-lane section was set much lower than that of the other two sections.

As drivers were asked to drive in the outside lane of the 2-lane section and in the left two lanes of the 3-lane section in the study, most of the data measured is limited to the left one or two lanes. Since the analysis results show that the LF/HF ratio tends to get higher while passing with a higher speed, drivers may get more stressed out when they drive in the inside lane for overtaking or passing. Therefore, data on driving stress in the inside lane should be checked for comparison analysis. Furthermore, driving stress tends to be relatively high on two-way two-lane expressways and in such special sections as sharp horizontal curves and tunnels. It is also desirable that locations and driving conditions where the stress evaluation indicator values increase are identified and analyzed in detail to improve the design of such facilities and traffic operation.

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