

Flow Structures above the Trunk Deck of Sedan-Type Vehicles and Their Influence on High-Speed Vehicle Stability

1st Report: On-Road and Wind-Tunnel Studies on Unsteady Flow Characteristics that Stabilize Vehicle Behavior

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ABSTRACT

This study shows an example in which the conventional aerodynamic evaluation method that focuses on “steady” aerodynamic lift coefficient is not necessarily sufficient to evaluate vehicle’s straight-ahead stability at high speed, and proposes a new aerodynamic evaluation method for vehicle stability.

In vehicle development, it is generally said that vehicle with lower aerodynamic lift coefficient has better straight-ahead stability at high speed. However, in some cases, straight-ahead stability differs between two vehicles with similar low aerodynamic lift coefficient. It is natural to think that this variation is caused by the difference of suspension characteristics or vehicle body rigidity. But from our experiences, different straight-ahead stability was observed between two vehicles having same suspension characteristics, same vehicle body rigidity and almost similar aerodynamic lift coefficient, but different vehicle configurations. A moving vehicle shows complex behaviors due to the unsteady aerodynamic forces caused by unsteady flow around the vehicle and unsteady vibration induced by undulated road. As aerodynamic lift coefficient simply indicates time-average, it could be considered that aerodynamic lift coefficient may not fully describe such complex vehicle behaviors during high speed driving.

Therefore, in this study, an attempt was made to clarify the relationship between unsteady flow around vehicle and straight-ahead stability, by investigating aerodynamic

forces generated from unsteady flow and its effects on vehicle behavior. Wind tunnel experiments and on-road driving experiments showed that vehicle straight-ahead stability is greatly influenced by a distinctive unsteady vortex structure above the trunk deck, and that a comprehensive aerodynamic technique based on unsteady characteristics of flow field is in need to evaluate vehicle’s straight-ahead stability in addition to the conventional steady aerodynamic approach.

INTRODUCTION

In vehicle aerodynamics development, aerodynamic lift coefficient has been accepted as the main index of high-speed running stability. However, few studies were conducted regarding the relationship between lift coefficient and high-speed stability. Buchheim et al. [1] investigated how the aerodynamic parameters (i.e., front axle lift coefficient C_{LF} , rear axle lift coefficient C_{LR} , and yawing moment coefficient C_{YM}) influence on the Stability Index (i.e., quantitative parameters for vehicle stability and controllability measured at fast highway driving, braking, and driving in a cross wind). Howell et al. [2] also compared the effects of C_{LF} and C_{LR} on the sensory rating of straight-ahead stability and lane-change maneuverability using several types of passenger cars. These studies concluded that a vehicle with overall-low lift level and negative pitching moment is desirable to improve high-speed stability. This theory is generally true, but little is known about the mechanism of how aerodynamic lift improves vehicle stability. It is natural to think that vehicle body lifts up and tires lose traction at

high lift coefficient. But lift force level appears not as significant as vehicle weight level, which is over 1t. For example, the lift coefficients of a vehicle at a speed of 200km/h (55.6m/s) with a frontal area of 2.0 m² are $C_{LF} = 0.1$ and $C_{LR} = 0.1$, representing lift forces of 378N (38.6kgf) each at its front and rear axles. On the other hand, from our experiences, straight-ahead stability could be greatly improved by modifying vehicle configuration to have very small difference in aerodynamic lifts (e.g. $\Delta C_{LR} \leq 0.005$, where ΔC_{LR} is the difference of C_{LR} value due to modification of vehicle configuration). The difference of $\Delta C_{LR} = 0.005$ represents only 18.9N (1.9kgf) in the difference between lift forces for a vehicle with a frontal area of 2.0 m² at 200km/h speed. In some cases in vehicle development, aerodynamic lift coefficient is not always a sufficient index to evaluate the high-speed straight-ahead stability of a vehicle. Aerodynamic lift coefficient is a time-averaged value measured in wind tunnel with fixed vehicle attitude against the ground. But as moving vehicle is exposed to unsteady aerodynamic forces generated by unsteady flow around the vehicle and unsteady vibration induced by undulated road, such vehicle's behavior is thought to be extremely complex. It could be considered that aerodynamic lift coefficient may not be capable of fully describing the complex vehicle behavior during high speed driving.

This study attempts to clarify how the unsteady flow around vehicle body influences on vehicle stability with a focus on high-speed straight-ahead stability. First, the vertical motion of vehicle body and the aerodynamic force affecting on vehicle body were measured in on-road driving experiments. Secondly, flow structure around vehicle body was investigated in wind tunnel experiments and numerical simulations. Finally, the unsteady flow structure stabilizing the vehicle's vertical motion was identified from both wind tunnel and on-road experiments.

EXPERIMENTAL METHOD

In this study, four mid-size sedan type production vehicles, shown in Fig. 1, were selected as the test objects. In order to investigate the relationship between unsteady flow around vehicle and straight-ahead stability, Vehicle-A (Fig. 1a) and Vehicle-B (Fig. 1b) were analyzed in on-road and wind tunnel experiments. However, the difference in straight-ahead stability between Vehicle-A and Vehicle-B could be caused not only by the difference in flow structure, but also by the difference of suspension characteristics and vehicle body rigidity. Thus, in order to investigate only the effect of the different flow structures on straight-ahead stability, Modified Vehicle-A (Fig. 1c) was also analyzed in on-road and wind tunnel experiments. Modified Vehicle-A is a model installed with eight types of additional parts in Vehicle-A to improve straight-ahead stability. In the process of investigating the relationship between unsteady flow around vehicle and straight-ahead stability, it was clarified that a vortex structure generated at the front pillar has some influence on straight-ahead stability.

Therefore, in order to investigate the front-pillar vortex structure, Vehicle-C (Fig. 1d) was analyzed in wind tunnel experiment.

The on-road experiments were conducted at the high-speed circuit in Mazda Motor Corporation Miyoshi Proving Ground. The circuit has a total length of 4.3km and consists of 3 straights and 3 bends. At this circuit, the fluctuation of ride height and static pressure on vehicle surface were measured concurrently while driving at 180km/h. The measuring positions of ride height and surface static pressure are shown in Fig. 2. The fluctuation of ride heights was measured using laser height sensors placed at front end and rear end. Ride heights were set to zero with vehicle stationary on horizontal ground. Surface static pressure fluctuation was measured at a sampling rate of 125Hz using surface static pressure disk probes located on vehicle surfaces, as shown in Fig. 2. Additionally, total pressure fluctuation above the trunk deck was measured at a sampling rate of 3.9Hz using $\phi 10\text{mm}$ Kiel probes. The

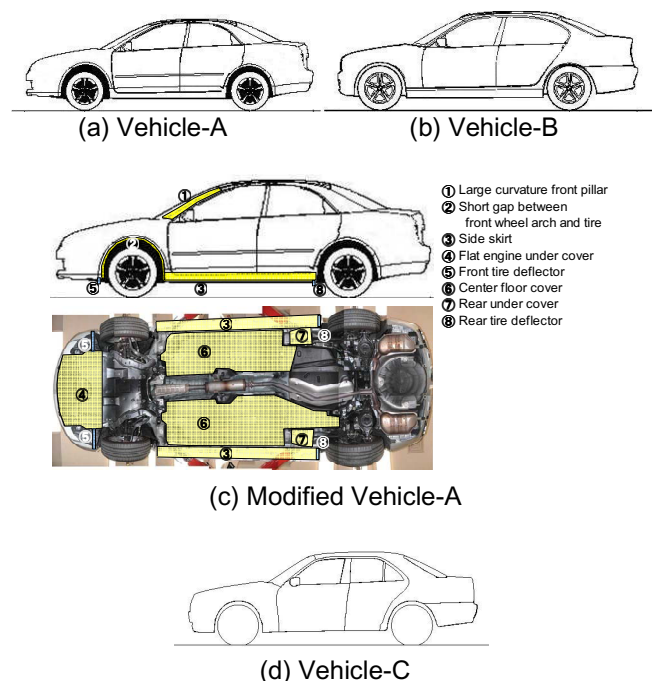


Fig.1 Testing models used in current study

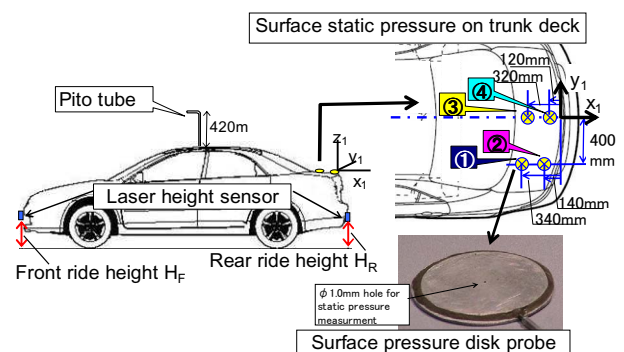


Fig.2 Measuring positions of ride height and surface static pressure

Kiel probes were placed on X-constant section on the trunk deck, where X-axis is defined as main flow direction in coordinate system. The number of the total pressure measurement points was 25 (5 points in horizontal direction $\times$ 5 points in vertical direction), at intervals of 50mm. Scanivalve Corporation Zoc33 was used to measure the absolute value of pressure fluctuation.

The wind tunnel experiments were conducted in a Göttingen-type Mazda Motor Corporation Wind-Tunnel. The dimension of the test section is 6m (width) $\times$ 4m (height) $\times$ 12m (length). A more detailed description about this facility could be found in Ref. [3]. In this wind tunnel, pressure and velocity were measured to analyze flow fields around the test vehicles. Time-averaged total pressure and surface static pressure were measured with the same equipments used in the on-road experiment. The velocity was measured using I-type hot-wire anemometers mounted on a traversing device. Furthermore, the flow was visualized with PIV and tuft method. Nexas9000 system was used to measure the two-dimensional velocity vector distribution at X-constant section.

NUMERICAL METHOD

In addition to experimental study, CFD simulation was also conducted to analyze flow field around Vehicle-A. In order to analyze the flow structure in respect of the vehicle high speed stability, it is required to predict the unsteady flow structures around the entire vehicle body including under body and engine compartment. Therefore, a commercial code FrontFlow/Red optimized for aerodynamics [4] has been applied in this study. This method based on finite volume method using unstructured tetrahedron mesh, enabled the modeling of the complex geometries of under body and engine compartment, as shown in Fig. 3. The CFD simulation

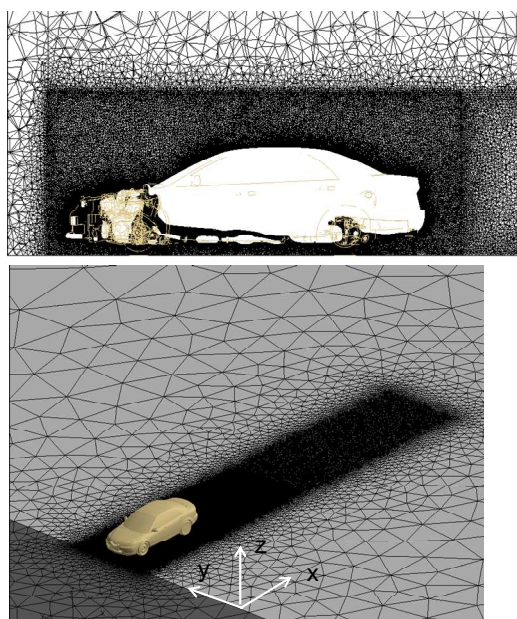


Fig.3 The grid for computational simulation of vehicle-A

was conducted on “Earth Simulator” which enables large-scale LES calculations with a hundred million computational meshes. Summary of the computational method in this study is shown in Table 1. The details of the method are abbreviated here.

RESULTS AND DISCUSSION

AERODYNAMIC EFFECT ON STRAIGHT-AHEAD STABILITY AND FLOW AROUND VEHICLE REAR BODY

First of all, aerodynamic influence on straight-ahead stability at high speed driving was investigated by measuring vehicles' vertical motion and unsteady aerodynamic forces acting on vehicle body on road. Next, flow fields around the vehicles were investigated.

Aerodynamic effects on straight-ahead stability

On-road investigation was conducted using two vehicle specifications with different straight-ahead stability. For the purpose of removing the influence of suspension characteristic and vehicle body rigidity variation, these two specifications were produced by configuring different shapes in a same vehicle. The first specification is Vehicle-A (Fig. 1a) which is a mid-size sedan type production vehicle. The other specification is Modified Vehicle-A (Fig. 1c) which was installed eight types of parts on Vehicle-A in an attempt to improve straight-ahead stability. As a result, sensory rating of straight-ahead stability improved with Modified Vehicle-A as shown in Fig. 4. Table 2 shows C_{LF} , C_{LR} , and C_D values of the two vehicles measured in wind tunnel. Rear axle lift coefficient C_{LR} slightly decreased with Modified Vehicle-A, but the difference of lift coefficient $\Delta C_{LR}=0.04$ represents only 129N (13.2kgf) lift force difference at a speed of 180km/h (50m/s).

In order to clarify the aerodynamic influence on straight-ahead stability, the fluctuations of ride height and surface static pressure of Vehicle-A and Modified Vehicle-A were measured in on-road driving. Fig. 5 shows the ride

Table 1 Summary of computational methods

Governing Equations	Filtered incompressible Navier-Stokes Equations
Turbulent Model	Smagorinsky SGS Model ($C_s=0.15$)
Convective discretization scheme	3rd order upwind
Time integration method	2nd order Adams-Bashforth(SMAC)
Discretization method	Finite volume method
Model Structure	Unstructured tetrahedrons
Model Size	37.9Million mesh elements
Boundary Condition	
Inflow	Fixed value
Outflow	Free outflow
Body/tire/ground wall Surface	Log-law
Simulation Solver	Front Flow/Red [4]
Calculation computer resource and statistics	
Hardware	Earth simulator
Nodes	64 (512CPU)
Memory size	303GB
Calculation time (real time)	28.8 Hours

height fluctuation H of Vehicle-A and Modified Vehicle-A measured in one-rap driving on the high-speed circuit at 180km/h. In these figures, H_F , H_R , and t denote front ride height, rear ride height, and time, respectively. The results in Fig. 5 include the impacts of running on up slope, down slope, and bends. Looking to the fluctuation level of both vehicles, the rear ride height of Vehicle-A (Fig. 5a) is higher than that of Modified Vehicle-A (Fig. 5b) at the moments shown in Fig. 5a and 5b by arrows. This difference of rear ride height is considered to be related with the difference of straight-ahead stability rating. However, this rear ride height difference of approximately 10 to 20mm appears to be too large even allowing for the difference of time-averaged lift coefficient $\Delta C_{LR} = 0.04$ and suspension characteristics of Vehicle-A. It could be assumed that this rear ride height difference was caused by unsteady aerodynamic force acting on vehicle body. Therefore, the fluctuation of surface static pressure was also measured.

Fig. 6 shows the fluctuation of rear ride height and surface static pressure C_p on trunk deck measured while running on straight, level section of the circuit

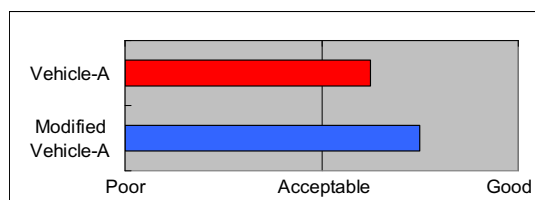
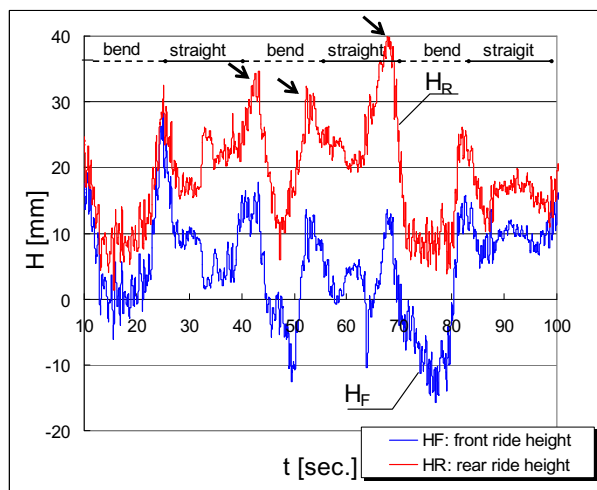


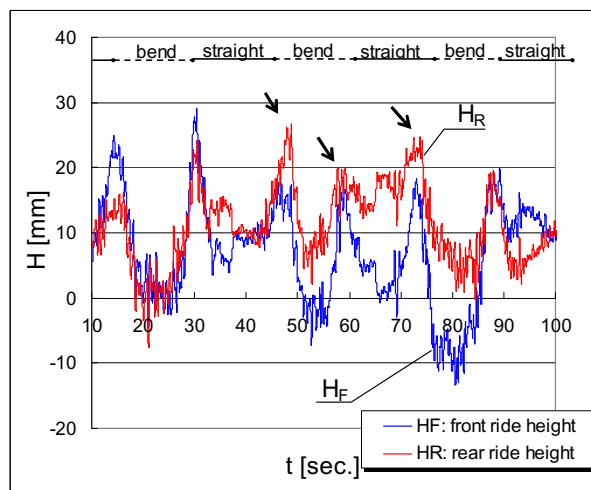
Fig.4 Sensory rating of straight-ahead stability (180km/h)

Table.2 Vehicles aerodynamic data

	C_{LF}	C_{LR}	C_D
Vehicle-A	0.09	0.11	0.32
Modified Vehicle-A	0.09	0.07	0.30

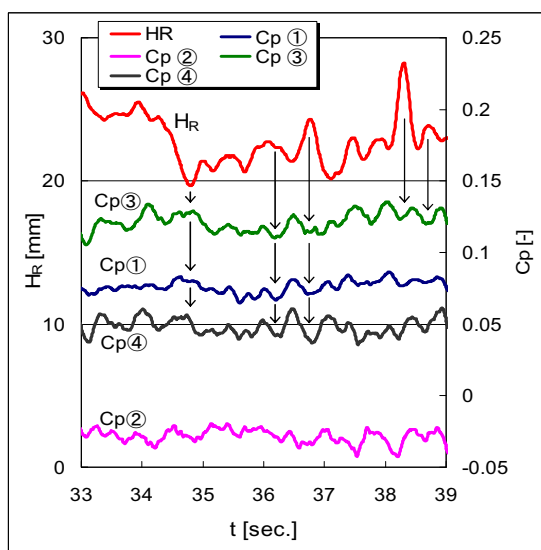


(a) Vehicle-A

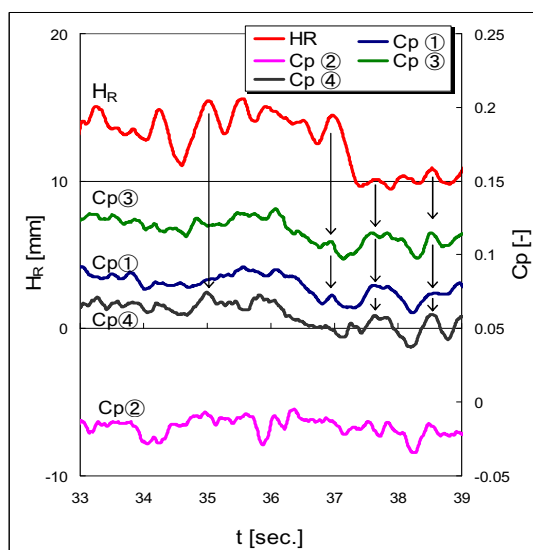


(b) Modified Vehicle-A

Fig.5 Fluctuation of ride height measured in a one-rap high-speed circuit driving



(a) Vehicle-A

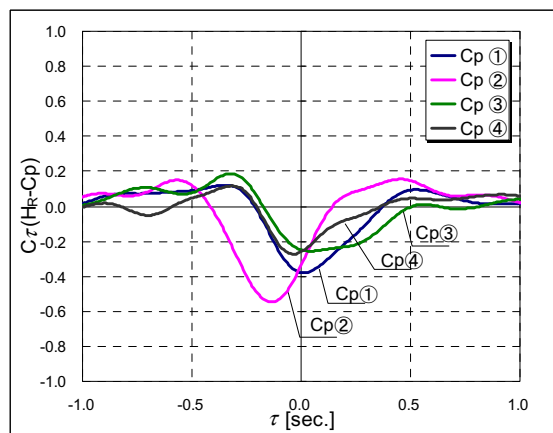


(b) Modified Vehicle-A

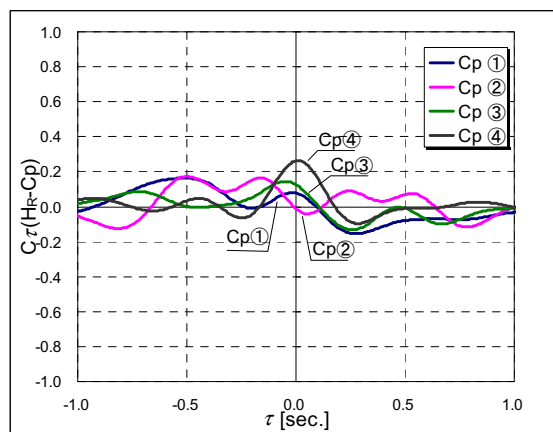
Fig.6 Fluctuation of rear ride height and surface static pressure on trunk deck measured while driving on straight, level section of the circuit

test track. This figure is a close-up of the rear ride height fluctuation during the time interval between 33 and 39 sec. on a straight, level section in Fig. 5, with surface static pressure fluctuation added. The fluctuations of rear ride height and surface static pressure show oscillation of approximately 2 Hz in both vehicles. Comparing the phase of these oscillations, the following trends were slightly seen: For Vehicle-A (Fig. 6a), the surface static pressure on trunk deck decreased while rear ride height increased, but for Modified Vehicle-A (Fig. 6b), the surface static pressure increased while rear ride height increased, as the arrows in Fig. 6a and 6b show, respectively. It could be considered that there is some correlative relationship between the fluctuations of rear ride height and surface static pressure. Next, this possible correlative relationship was analyzed statistically.

Fig. 7 shows the cross correlation coefficient $C\tau(H_R-C_p)$ between the fluctuation of rear ride height and each surface static pressure on trunk deck measured while running on a straight, level section. In these figures, τ denotes lag time. Fig. 7a shows trunk deck surface static pressure of Vehicle-A correlating at negative values from -0.55 to -0.2 around $\tau = 0$. These negative values of cross correlation suggest surface static



(a) Vehicle-A



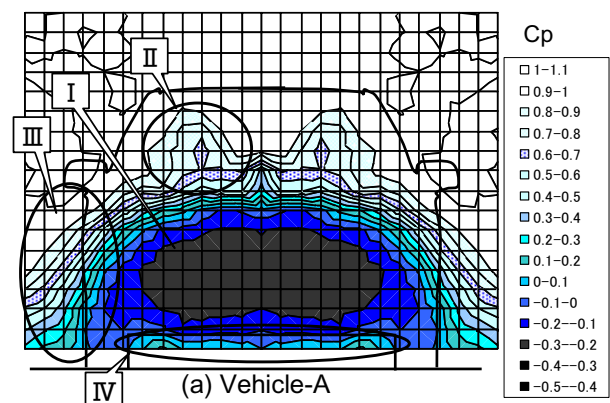
(b) Modified Vehicle-A

Fig.7 Cross correlation coefficient between rear ride height and surface static pressure on trunk deck measured while driving on straight, level section of the circuit

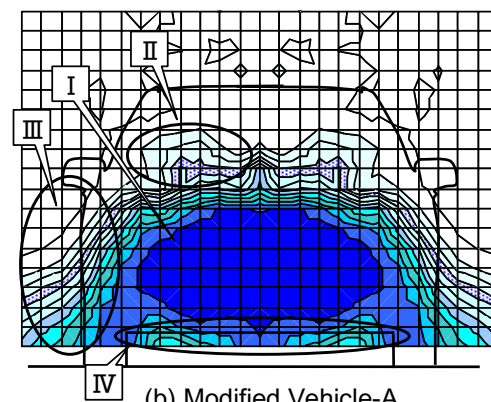
pressure on trunk deck had decreased while rear ride height increased, thus it could be considered that aerodynamic force had acted on trunk deck to promote vertical motion of Vehicle-A. Fig. 7b shows trunk deck surface static pressure of Modified Vehicle-A correlating at low but positive values from +0.1 to +0.25 around $\tau = 0$. These low positive values of cross correlation suggest surface static pressure on trunk deck had slightly increased while rear ride height increased. Thus, it could be considered that aerodynamic force had acted on trunk deck to slightly restrain vertical motion of Modified Vehicle-A. It could be assumed that the difference in vehicle stability was caused by this difference of aerodynamic force on trunk deck, either promoting or restraining vehicles' vertical motion. Next, in order to identify what has caused the difference in aerodynamic force on trunk deck of Vehicle-A and Modified Vehicle-A, the flow structures around rear body of both vehicles were compared.

Flow around vehicle rear body

Fig. 8 shows the total pressure distribution at 250 mm behind the vehicles measured in wind tunnel experiment. Total pressure of the left half of the vehicle was measured and a mirror copy of the left half was added to the right side in Fig. 8. In these figures, total pressure loss could be observed in region "I," behind the trunk deck of each vehicle. It could be considered that flow energy loss had occurred due to a vortex or a turbulent



(a) Vehicle-A



(b) Modified Vehicle-A

Fig.8 Total pressure distributions at 250 mm behind vehicles

flow structure in the total pressure loss region. As it is generally known that trailing vortices exist behind vehicle and the strength of such vortices has an impact on the drag force behind the vehicle [5], [6], it could be considered that trailing vortices exist in region "I." The total pressure value in this region "I," was lower in Vehicle-A than in Modified Vehicle-A. Comparing the regions surrounding this total pressure loss region "I," the differences between the two vehicles were also seen in upper region "II," lateral side region "III," and lower region "IV." Total pressure loss in the upper region "II" was seen in both vehicles, and the area was larger in Vehicle-A than in Modified Vehicle-A. Total pressure loss in lateral side region "III" was seen in both vehicles, and the region "III" extends upward into wider area in Vehicle-A than in Modified Vehicle-A. A pair of slightly high total pressure areas in lower region "IV" was seen in both vehicles, but region "IV" extends laterally into wider area in Vehicle-A than in Modified Vehicle-A.

However, the flow structures existing in the total pressure loss region "II," "III," and "IV" are not clear. Before discussing the flow structure that promoted or restrained vertical motion of the vehicles in the on-road driving experiments, the flow structure around Vehicle-A and Modified Vehicle-A should be investigated and understood. Next, an attempt was made to clarify the flow structure around the vehicle body.

FLOW STRUCTURE AROUND VEHICLE BODY BASED ON VEHICLE-A

An attempt was made to clarify the flow structure around the vehicle body by respectively ascertaining how the total pressure loss regions "II," "III," and "IV" in Fig. 8 had emerged and behaved.

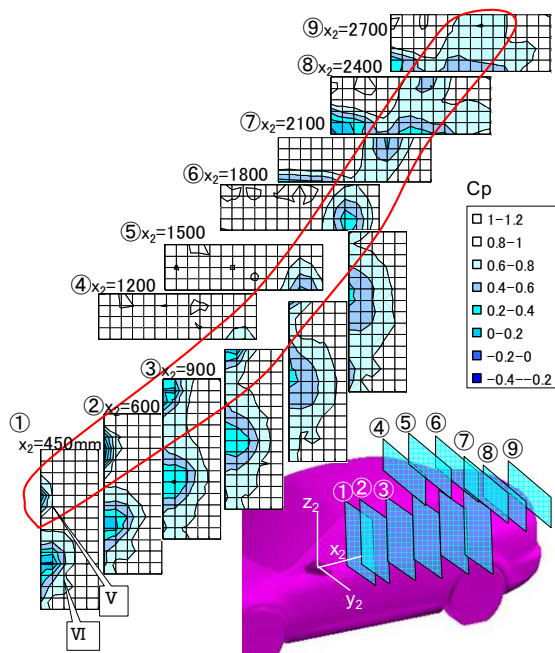


Fig.9 Total pressure distributions around upper half of Vehicle-A

Flow structure above vehicle body

First, total pressure loss of the upper region "II" in Fig. 8 was investigated. The total pressure distribution around the upper half of Vehicle-A was measured and shown in Fig.9. At section ①, total pressure loss could be seen behind front pillar ("V") and door mirror ("VI"). It seems that the total pressure-loss area behind the front pillar extends wider and upward beside the side window to the roof (section ④ to ⑥) as it travels downstream to the region above the trunk deck (section ⑧ and ⑨). Fig. 10 shows the flow streamlines of front pillar vortex in Vehicle-A, obtained from CFD. This streamlines show that the vortex separates from the front pillar, and travels downstream to the region above the trunk deck via the roof. Therefore, it could be assumed that the total pressure loss region behind the front pillar ("V" at section ① in Fig.9) represents the vortex separated from front pillar that traveled to the region above the trunk deck via roof. It could also be considered that the total pressure loss region "II" in Fig 8 represents the total pressure loss region traveled from behind the front pillar.

Due to the front pillar vortex at 250 mm above the trunk deck, it could be thought that it has an influence on the flow structure above the trunk deck. Therefore, the behaviors of front pillar vortex of different intensities were compared to clarify its influence on the downward flow structure. Vehicle-C was used to observe fairly weak front pillar vortex, and then it was remodeled to observe strong front pillar vortex. The configurations of the front pillar of both vehicles are shown in Fig. 11.

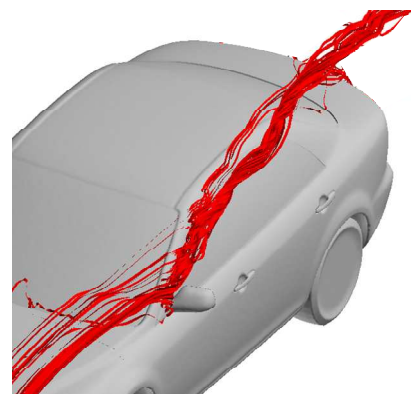


Fig.10 Flow streamlines of front pillar vortex obtained from CFD (Vehicle-A)

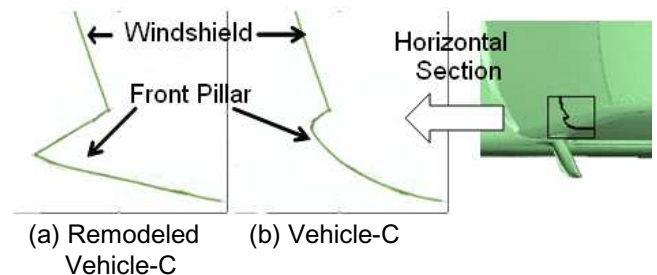


Fig.11 Remodeling to front pillar of Vehicle-C