

Prediction formula of Aerodynamic Drag Reduction in Multiple-Vehicle Platooning Based on Wake Analysis and On-Road Experiments

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ABSTRACT

An experimental study on reducing aerodynamic drag and improving fuel economy through vehicle platooning was conducted to develop an Intelligent Transport System (ITS) with good fuel economy of the entire vehicle-based transportation society. The objectives of the present study are to achieve a simple and quick approach to estimating the aerodynamic drag reduction rates of vehicle platooning. This paper reports the prediction formula, including the conditions of various types of vehicles in multiple-vehicle platooning, based on the power law of a free turbulent axisymmetric wake and on-road experimental results. Note, the prediction formula in this study does not fully include the effect of various type of wake deficit patterns due to rear shape of vehicle and atmospheric wind. Therefore, continuous study is needed to examine the applicable limit.

CITATION: Tadakuma, K., Doi, T., Shida, M., and Maeda, K., "Prediction formula of Aerodynamic Drag Reduction in Multiple-Vehicle Platooning Based on Wake Analysis and On-Road Experiments," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(2):2016, doi:10.4271/2016-01-1596.

1. INTRODUCTION

Improving automobile fuel economy is one of the most important issues in conserving energy and improving the global environment. In addition to efforts to improve the fuel economy of individual vehicles, development is also underway to improve the fuel economy of groups of vehicles by reducing aerodynamic drag through vehicle platooning based on Intelligent Transport System (ITS) technologies.

Examples of past studies in the U.S. related to fuel economy improvement through platooning include the PATH Program [1, 2, 3], which studied platooning two to four vehicles (sample vehicles: sedans, trucks, etc.). In Europe, bus-bus platooning [4], and a project is underway, called the "Safe Road TRains for the Environment (SARTRE)", that is attempting to identify the benefits of platooning (emissions reduction on highways and safety improvement) [5, 6, 7, 8]. Other studies include those that examined fuel economy improvement during the platooning of various types of vehicles under on-road conditions, or used Computational Fluids Dynamics (CFD) and wind tunnels to study the effects of inter-vehicle distance and the shape of the leading vehicle during platooning on the aerodynamic drag on the trailing vehicles, as well as the changes in the vehicle wake [9, 10, 11, 12].

While many useful studies have been carried out, to the best of the authors' knowledge, very few studies have empirically investigated the aerodynamic drag reduction effects of platooning using actual vehicles in on-road condition, and no attempt has been made to predict these effects analytically.

Therefore, the purposes of this study were to identify the aerodynamic drag reduction effects of platooning and to make it simple to predict these effects. This study can be expected to make it possible to assess the aerodynamic drag reduction rates that correspond to the inter-vehicle distance, etc. without conducting on-road tests in advance.

2. PAST STUDIES AND THIS STUDY

To measure and predict the aerodynamic drag reduction rate of platooning, it is postulated that the effects of the following four factors must be considered:

1. Inter-vehicle distance
2. Lateral position
3. Natural wind
4. Number of vehicles in the platoon



An earlier study examined the effects of factors (1), (2), and (3) on a 2-vehicle platoon of actual vehicles in an on-road experiment, clarifying the aerodynamic drag reduction effects and constructing a prediction formula for the aerodynamic drag reduction effects on the following vehicle [13, 14]. With regard to the effect of the number of vehicles in the platoon (4), actual vehicles were used in an experiment to clearly identify the aerodynamic impact and create a prediction formula for the aerodynamic drag reduction during platooning of N vehicles (three or more) [15].

However, the prediction formula for the aerodynamic drag reduction effects during multi-vehicle platooning suggested in the earlier study was applicable only to cases involving vehicles of the same type and equal inter-vehicle distances. That is, the prediction formula suggested in the earlier study was not generalized enough to estimate the effects in an on-road environment.

Therefore, referencing the results obtained from earlier experiments using actual vehicles and studies on the wake behind a body of revolution [16, 17], this paper reports the construction of a prediction formula for the aerodynamic drag reduction rates during multi-vehicle platooning that takes into account different vehicle types and different inter-vehicle distances.

First, the experimental method in on-road, results and discussion of the flow field in 3-vehicle platoon [15] are described in section 3. Second, the approach to constructing a prediction formula for aerodynamic drag reduction rate during multiple vehicles of the same type is discussed in Section 4. Then, Section 5 describes the construction of a formula that can predict the aerodynamic drag reduction rate even when a platoon contains different vehicles types and the inter-vehicle distance varies.

3. AERODYNAMIC DRAG REDUCTION RATE AND PRESSURE DISTRIBUTION ON A FOLLOWING VEHICLE IN 3-VEHICLE PLATOON

3.1. Experimental Method [15]

The aerodynamic force of the vehicle was evaluated by the integration of the surface pressure on the vehicle with respect to the projected frontal area in 3-vehicle platooning and solo driving, respectively. The rate of the aerodynamic drag reduction is determined by comparing the coefficient of the pressure drag between solo driving and the platooning.

Figure 1 shows a sedan-type test vehicle. Test course has a long straight path which can keep the sufficient time for the measurement.

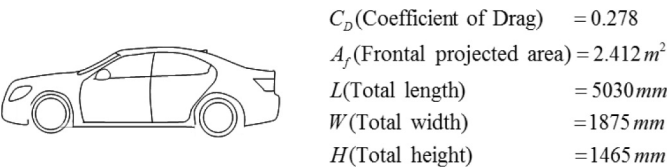


Figure 1. Test vehicle.

Table 1. Test cases.

Measurement object	Velocity (km/h)	x_{12} (m)	x_{23} (m)
Solo driving	100	-	-
2 nd Vehicle	↑	10	10
↑	↑	15	15
↑	↑	20	20
↑	↑	30	30
3 rd vehicle	↑	10	10
↑	↑	30	30

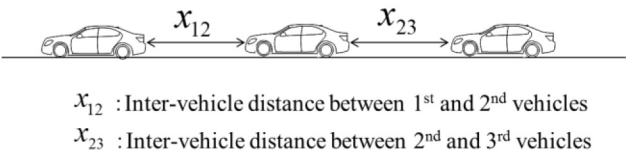


Table 1 shows test cases. Solo driving was conducted to measure a reference data on aerodynamic drag by using the vehicle of the sedan type with instrumentation.

The combination of same-type three cars for platoon driving is 2 sedan cars and a sedan car with instrumentation. The distance between cars is varied from 10m to 30m in 100 km/h steady driving.

The sedan-car with instrumentation measured the pressure on the vehicle, vehicle speed and the vehicle distance. The leading sedan car has a 3-hole pitot tube to calculate the wind direction and the dynamic pressure, including the natural wind, affecting the test cars.

Figure 2 shows the 3-hole pitot tube and the view installed into the test car. The 3-hole pitot tube can be determined an angularity and velocity. The natural wind has a large aerodynamic effect when the aerodynamic data is measured in on-road testing. That is why it is important to obtain the angularity and the velocity of the natural wind. The 3-hole pitot tube was calibrated by wind tunnel test in advance for calculating the angularity and the velocity to the leading vehicles with the 3-hole probe pitot tube.

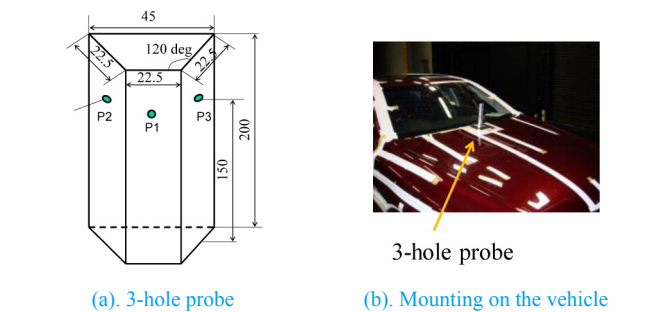


Figure 2. 3-hole probe.

Figure 3 shows the location of the pressure measurement on the sedan car with instrumentation. The difference pressure between the points and the interior was measured.

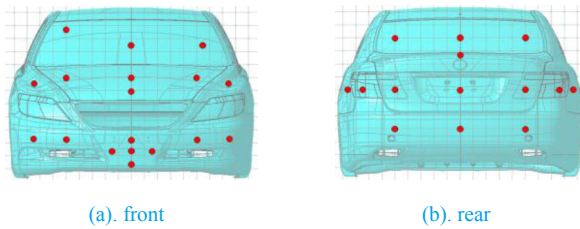


Figure 3. Pressure holes arrangement.

The velocity of the test vehicles was obtained from the ECU (Electric Control Unit) data through the CAN (Controller Area Network). The vehicle distance was measured by using the RADAR of the following vehicle. The lateral position was determined that the leading and the following vehicles measured the line edge of the road respectively. The weather date, temperature, humidity, atmosphere pressure and angularity and velocity of the natural wind, was measured near the test course.

The on-road experiments were conducted when the natural wind is less than 3 m/s. Then, the experiment data that the yaw angle measuring at 1st vehicle is less than 2 degree was used to evaluate the aerodynamic drag reduction rate and the pressure distribution.

3.2. Results of Aerodynamic Drag Reduction Rate and Pressure Distribution

Figure 4 shows the aerodynamic drag reduction rate for the second vehicle, third vehicle in 3-vehicle platoon [15] and the first vehicle in a 2-vehicle platoon [13].

Figure 5 to Figure 7 show the pressure coefficient distribution of the second vehicle in 3-vehicle platoon. Figure 5 shows the results of whole measured pressure locations in front and the back, Figure 6 and 7 are enlarged to be easily understandable the change due to the inter-vehicle distance.

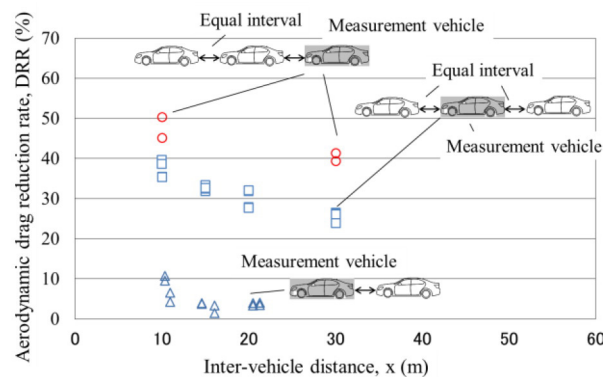


Figure 4. Results of aerodynamic drag reduction rate in 3-vehicle platoon.

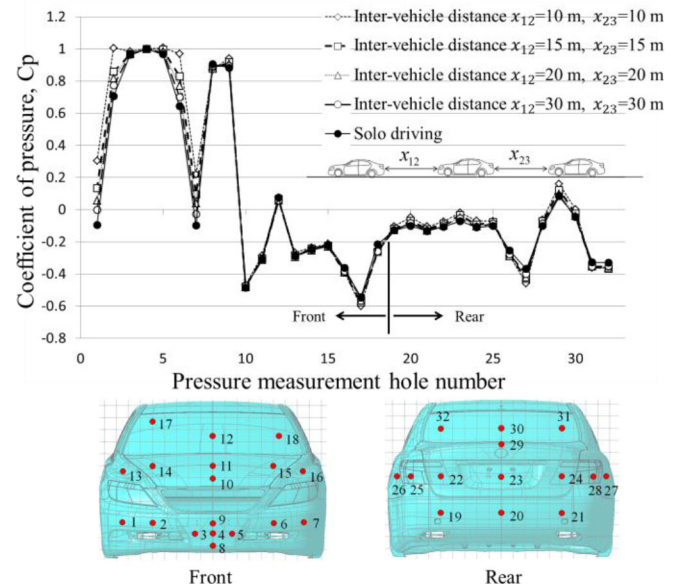


Figure 5. Results of pressure coefficient of second vehicle in 3-vehicle platoon.

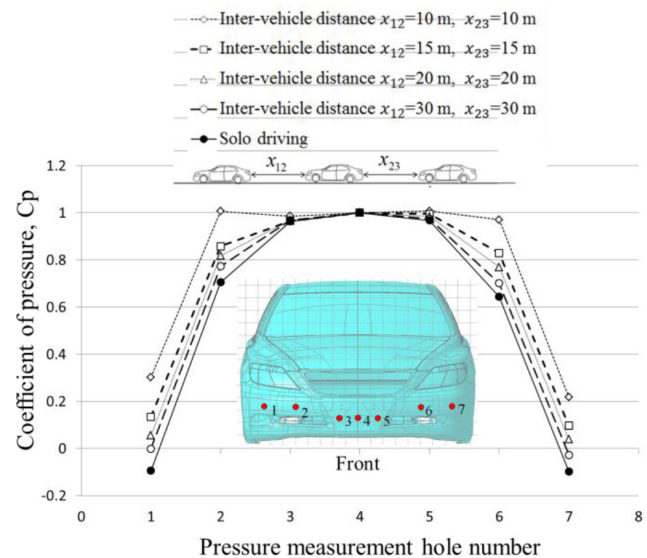


Figure 6. Results of pressure coefficient of second vehicle in 3-vehicle platoon.

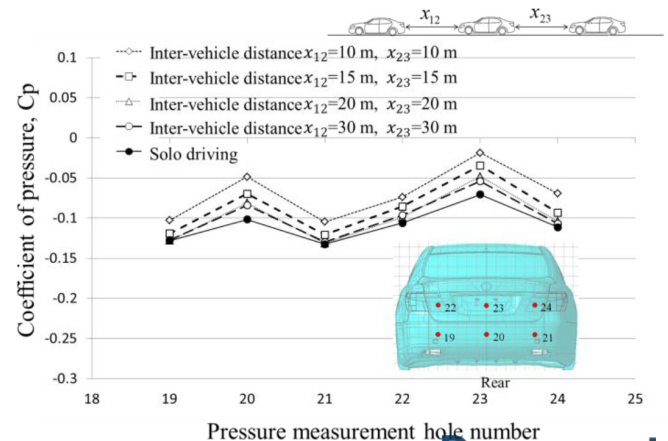


Figure 7. Results of pressure coefficient of second vehicle in 3-vehicle platoon.

3.3. Discussion for Constructing a Prediction Formula

From Figure 6, the pressure distribution affected on the front surface is getting closer to that of the solo driving as the inter-vehicle distance moves from 10m to 30m. When the inter-vehicle distance is 10m, the pressure coefficient of the both ends in span-wise direction of the second vehicle is larger than that of the solo driving. This is because, as the inter-vehicle distance decreases, the flow velocity distribution becomes non-uniform like a flow as having a span-wise parabolic velocity distribution for the second vehicles.

From Figure 7, the pressure distribution affected on the rear surface is getting closer to that of the solo driving as the inter-vehicle distance moves from 10m to 30m as same tendency as the distribution of the front.

4. APPROACH TO CONSTRUCTING A PREDICTION FORMULA FOR AERODYNAMIC DRAG REDUCTION FROM PLATOONING

As discussed in Section 3, considering the results of 3-vehicle platoon, the approach to constructing a prediction formula for aerodynamic drag reduction rate during the platooning of multiple vehicles of the same type is discussed [13, 14, 15].

4.1. Reduction in the Aerodynamic Drag of each Vehicle in a 2-Vehicle Platoon

4.1.1. Second Vehicle in a 2-Vehicle Platoon

Figure 8 shows a schematic view of vehicle wake. Vehicle wake expands as its rearward distance from the vehicle increases, and the velocity distribution becomes increasingly smooth and flat. Because the trailing vehicle travels inside the wake of the leading vehicle, the dynamic pressure applied to the trailing vehicle is decreased, thereby reducing the aerodynamic drag on it [13].

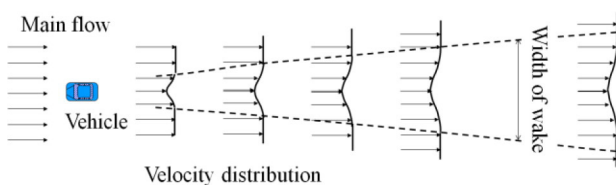


Figure 8. Schematic view of vehicle wake [13,16, 17].

The velocity distribution of the wake caused by the leading vehicle becomes more smooth and flat as the inter-vehicle distance increases, approaching a uniform flow for a second vehicles as described in 3-vehicle-platoon experiment in Section 3. Within the range in which the wake can be considered approximately uniform, that means the pressure coefficient distribution of a following vehicle is almost same as that of the solo driving, when an inter-vehicle distance is more than 30m as described in 3-vehicle-platoon experiment in Section 3, it should be possible to determine the aerodynamic drag reduction rate by comparing the dynamic pressure applied to the trailing vehicle with the dynamic pressure applied during solo driving.

How to determine the dynamic pressure applied to the following vehicle is considered. As for the presence of the ground, it is moving at the same velocity as the vehicle in relative terms and therefore, the vehicle wake is presumed to exhibit the same velocity distribution as the wake caused by a body of revolution inside a spatially uniform flow. Therefore, referencing a study related to the free turbulent axisymmetric wake [16, 17], it was postulated that the dynamic pressure applied to the trailing vehicle could be determined by determining the vehicle-center-line deficit velocity.

In the earlier study on that presumption, prediction formulas related to the aerodynamic drag reduction rate on the second vehicle in a 2-vehicle platoon were constructed based on the above approach (Equations (1) through (3)) [13].

$$\xi_1 = a C_{D1}^b \left(x_{12} / A_{f1}^{1/2} \right)^{-2/3} \quad (1)$$

$$U_{2,min} / U_1 = 1 - \xi_1 \quad (2)$$

$$DRR_2 = 1 - (1 - \xi_1)^2 \quad (3)$$

Here, ξ_1 is the maximum deficit velocity rate inside the wake from the first vehicle; a is a coefficient ($a = 1.05$); C_{D1} is the coefficient of drag of the first vehicle; b is a coefficient ($b = 0.2$); x_{12} is the distance between the first and second vehicles [m]; A_{f1} is the frontal projected area of the first vehicle [m²]; $U_{2,min} / U_1$ is the ratio between the center-line velocity received by the second vehicle and the main flow received by the first vehicle; and DRR_2 (Drag Reduction Rate) is the aerodynamic drag reduction rate for the second vehicle. Coefficients a and b were calculated based on empirical results in on-road experiments.

However, as the inter-vehicle distance decreases, the flow velocity distribution is no longer flat and becomes non-uniform like a flow as having a span-wise parabolic velocity distribution for the second vehicles, as inferred by the 3-vehicle-platoon experiment in Section 3. Consequently, it becomes difficult to determine the aerodynamic drag reduction rate using the dynamic pressure ratio shown in Equations (1) through (3), and correction related to the non-uniformity of the flow is necessary.

Figure 9 shows empirical results on the relationship between the increase $\Delta C_{Dpf} / C_{Dp,solo}$ in the coefficient of forebody pressure drag due to the non-uniform flow and the inter-vehicle distance [15]. These results were obtained by integrating the pressure distribution on the front surface of test vehicles as shown in the 3-vehicle-platoon experiment in Section 3. Here, the definition of ΔC_{Dpf} and $C_{Dp,solo}$ is shown Figure 9. As for the meaning ΔC_{Dpf} when $\Delta C_{Dpf} = 0$, the pressure coefficient distribution on the front of a following vehicle is same as that of the solo driving.