

AERODYNAMIC EFFECT OF ROOF-FAIRING SYSTEM ON A HEAVY-DUTY TRUCK

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ABSTRACT—Aim of this study is to investigate an aerodynamic effect of a drag-reducing device on a heavy-duty truck. The vehicle experiences two different kinds of aerodynamic forces such as drag and uplifting force (or downward force) as it is traveling straight forward at constant speed. The drag force on a vehicle may cause an increase of the rate of fuel consumption and driving instability. The rolling resistance of the vehicle may be increased as result of the negative uplifting or downward force on the vehicle. A device named roof-fairing system has been applied to examine the reduction of aerodynamic drag force on a heavy-duty truck. As for a engineering design information, the drag-reducing system should be studied theoretically and experimentally for the best efficiency of the device. Four different types of roof-fairing model were considered in this study to investigate the aerodynamic effect on a model truck. The drag and downward force generated by vehicle has been obtained from numerical calculation conducted in this study. The forces produced on four fairing models considered in this study has been compared each other to evaluate the best fairing model in terms of aerodynamic performance. The result shows that the roof-fairing mounted truck has bigger negative uplifting or downward force than that of non-mounted truck in all speed ranges, and drag force on roof-fairing mounted truck has smaller than that of non-mounted truck. The drag coefficient (C_D) of the roof-fairing mounted truck (Model-3) is reduced up to 41.3% than that of non-mounted trucks (Model-1). A downward force generated by a roof-fairing mounted on a truck is linearly proportional to the rolling resistance force. Therefore, the negative lifting force on a heavy-duty truck is another important factor in aerodynamic design parameter and should be considered in the design of a drag-reducing device of a tractor-trailer. According to the numerical result obtained from present study, the drag force produced by the model-3 has the smallest of all in all speed ranges and has reasonable downward force. The smaller drag force on model-3 with 2/3h in height may results of smallest thickness of boundary layer generated on the topside of the container and the lowest intensity of turbulent kinetic energy occurs at the rear side of the container.

KEY WORDS : Roof-fairing, Aerodynamic drag force, Lift force, Down force, Road-load power, Rolling resistance force, Engine brake power, Turbulent kinetic energy

1. INTRODUCTION

When a vehicle runs on a road at the constant cruising speed, it has to overcome two types of external forces to maintain its speed constant. These are the rolling resistance on a road and aerodynamic drag force acting on the body. In the case of rolling resistance force, it has an effect on the driving stability of the vehicle but the aerodynamics drag force is directly related to the rate of fuel consumption of the vehicle engine. Especially for fuel economy and environmental protection from the automobile emissions, an aerodynamic drag-reducing device has been designed and applied to the road vehicles. In this study, an aerodynamic characteristics of the roof-fairing system is numerically studied to find out

its effect on a tractor-trailer. From the previous experimental studies (William *et al.*, 1975; Lee *et al.*, 1997; Lee *et al.*, 1982), a fairing system was proven as an effective device for the reduction of aerodynamic drag on a long distance, high speed traveling truck.

In this study, four different types of roof-fairing system were used to examine their aerodynamic effects on a model vehicle. Three of them have flat-plate shapes in the front side of the fairing but each has different size in height to see the effect of the installation height on the aerodynamic performance of the vehicle. The other one has a rounded shape on top with a fixed height. The speed of the model vehicle was varied from 30 km/h to 150 km/h to investigate the effect of speed on the aerodynamic performance of the roof-fairing system on the vehicle.

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2. AERODYNAMIC CHARACTERISTICS AND GEOMETRY OF MODEL TRACTOR-TRAILER

2.1. Aerodynamic Characteristics of Tractor-Trailer

The power required to drive a vehicle at a constant speed on a road consists of two kinds of power that overcome an aerodynamic drag force and rolling resistance force, which may be called a road-load power required by a running vehicle. There are two kinds of aerodynamic force; drag and uplifting (or downward) force as a heavy-duty truck runs on a highway with no side-wind effect. Generally speaking, it is known that the drag force effects on driving power required and the lift force effects on driving stability of a truck. However, it was found that the majority of concept on an aerodynamic design of vehicle is to minimize the rate of fuel consumption for a heavy-duty truck (Kim *et al.*, 2000) and driving stability for a small size sedan (Kim *et al.*, 1998).

Figure 1 shows a complicated airflow phenomenon around a running truck on a road. Aerodynamic drag force generated on the vehicle is mainly the form or pressure drag force on a body. As shown in the figure, the fore coming air stream strikes on the front-side of the vehicle and contributes to increase the stagnation pressure which is one of the main cause of the form drag. Some air goes up through the roof of the body and some other is induced down to the ground and side of the body of the vehicle. The second part of the serious form drag is generated on the front facing wall of the container. As air stream passes through the top of the container, the stream is separated from the edge of the container roof and it contributes to increase the intensity of vortex generated at the rear side of the container. It is another source of the pressure drag on the body. Therefore, an aerodynamic

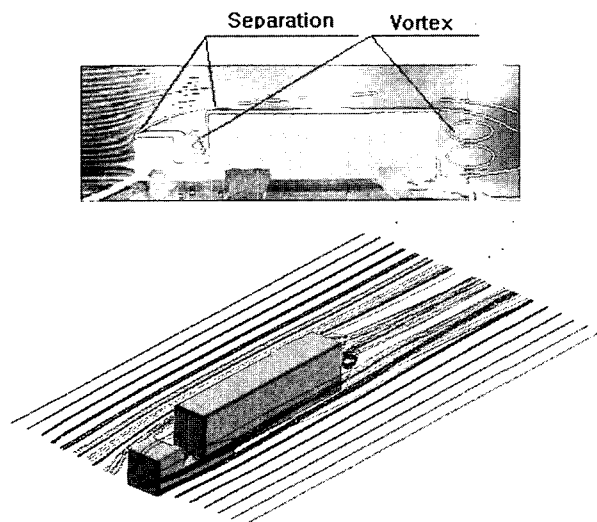


Figure 1. Airflow phenomenon around a heavy-duty truck.

drag reducing system can be applied to the vehicle to reduce the rate of fuel consumption.

The downward force that is generated on a running vehicle is due to the pressure difference between the top and the bottom side of the trailer. It affects to the engine power required by the truck because the downward force is linearly proportional to the rolling resistance generated on the tires of the vehicle.

As mentioned above, pressure drag or form drag and lift or downward force are two important physical forces that can be generated on a running vehicle. Therefore, a carefully consideration on these factors should be given in an optimum design of a roof fairing system of a tractor-trailer.

2.2. Geometry of Model Tractor-Trailer

Most popular model of a tractor-trailer operated for logistics industry in Korea was incorporated in the numerical study. The tractor (model-D8AB, 60 tons) is manufactured in Hyundai Motor Co. Korea and the trailer with chassis (model JCC-40XEE, 40ft) is from Jindo Co. Korea. The dimension and configuration of the tractor-trailer model is shown in Figure 2.

To minimize the computation time, the half of the model vehicle was used for 3-D modeling in numerical simulation because 3-D configuration of the model truck may be assumed quasi-symmetric along the dotted center-line and the boundary condition is assumed steady.

2.3. Aerodynamic Drag Reduction System of Truck

In general, there are three different ways to reduce drag force on a heavy-duty truck; a roof fairing system, gap sealing system and skirts system. However, a roof fairing system is considered in this study because it can be the most effective device to reduce the drag force of a heavy-duty truck (Barnard, 1996). The representative drag reducing systems installed on a heavy-duty truck is shown in Figure 3.

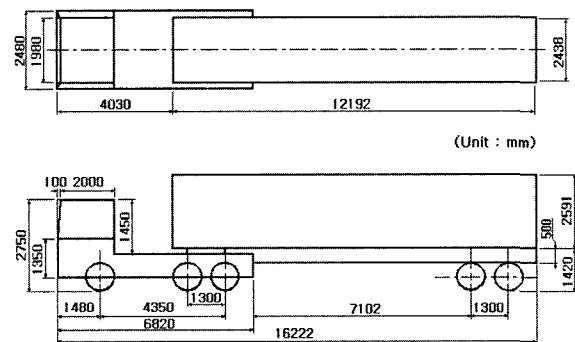


Figure 2. 2-Dimensional view of the model tractor-trailer and its dimension.

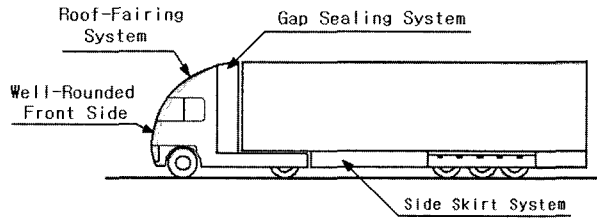


Figure 3. Representative drag reducing systems installed on a heavy-duty truck.

3. NUMERICAL SCHEME AND BOUNDARY CONDITIONS

In this study, FVM (Finite Volume Method) was employed to simulate airflow phenomenon around a tractor-trailer traveling on a road at a constant speed without side wind effect. Therefore, the airflow field of the control volume can be reasonably defined as ;

- Quasi-3D flow
- Steady state flow
- Incompressible flow
- Turbulent flow

The general-purpose CFD code, PHOENICS (ver.3.1), has been used for a numerical study of the turbulent incompressible flow field. 3-dimensional Navier-Stokes equations were solved with standard (κ - ϵ) turbulent model (Patankar, 1980). Since the process was assumed as steady state and adiabatic process, and thus the energy equation was not required to solve in the numerical calculation. The turbulent no-slip condition near solid boundary has been modeled by the logarithmic law. Time differencing has been fully implicit backward while advection terms are hybrid differenced. Conjugate gradient techniques for pressure corrections in transport equations has been incorporated and 'SIMPLE' algorithm (Patankar, 1980) has been employed for the velocity/pressure coupling in this application.

3.1. Governing Equations

The basic equations of fluid dynamics in the control volume are based on the Navier-Stokes equations that are comprised of equations for conservation of mass and momentum and given as,

(1) Continuity equation

$$\frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial y_j} + \frac{\partial U_k}{\partial z_k} = 0 \quad (1)$$

(2) Momentum equation

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} (U_i U_j) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \overline{u_i u_j} \right] - g_i \quad (2)$$

(3) Turbulent kinetic equation

$$\frac{\partial}{\partial x_i} (U_j k) = \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G - \epsilon \quad (3)$$

(4) Energy dissipation equation

$$\frac{\partial}{\partial x_i} (U_j \epsilon) = \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \frac{\epsilon}{k} (C_{\epsilon 1} G - C_{\epsilon 2} \epsilon) \quad (4)$$

where $\overline{u_i u_j} = \nu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}$

$$G = -\overline{u_i u_j} \frac{\partial U_i}{\partial x_j}, \quad \nu_t = C_\mu \frac{k^2}{\epsilon}$$

($C_\mu = 0.09$, $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\epsilon = 1.0$)

3.2. Numerical Grid of Physical Model and Boundary Conditions

BFC (Body Fitted Coordinates) grid generation method (Thompson, 1991) in conjunction with non-orthogonal grids allowing irregular geometries has been used to generate the numerical grid in this study. The optimum grid size of the 3-D model was found by $73 \times 34 \times 30$ from the validation test of numerical grid. Figure 4 shows a typical 2-D numerical grid of the model truck without a fairing system incorporated for this numerical study.

Boundary and initial conditions of the calculation:

- (1) Velocity boundary condition at the inlet of the control volume; $U_{car} = 30-150$ Km/h
- (2) Pressure boundary condition at the exit of the control volume
- (3) No-slip condition at the surface of the model tractor-trailer
- (4) Moving boundary condition on the surface of a road
- (5) Potential flow conditions on the open surface of the control volume; north, high and low surface

3.3. Major Parameters and Their Ranges

Height and shape of the fairing model and speed of the model truck are three important variables that may influence on the aerodynamic forces. Table 1 shows the major parameters and their ranges for the numerical study.

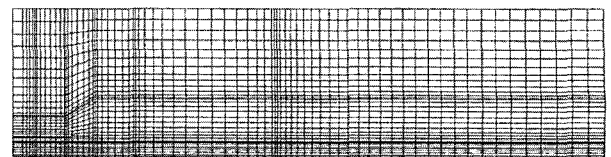
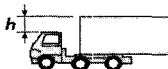


Figure 4. A typical numerical grid of the model tractor-trailer without a fairing system ($73 \times 34 \times 30$).

Table 1. Specification of the fairing and velocity of the tractor-trailer.

Model	Specification of fairing	
Model-1	No fairing (standard model)	<div>h is the height between trailer and container.</div> 
Model-2	Fairing height (h')= $1/3h$	
Model-3	Fairing height (h')= $2/3h$	
Model-4	Fairing height (h')= h	
Model-5	Rounded Fairing (h')= h	
Speed range of the tractor-trailer.		
U_{car} =30, 50, 80, 100, 120, 150 (Km/h)		

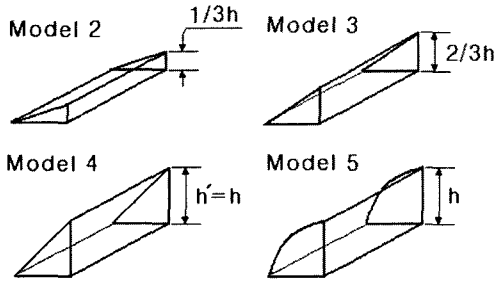


Figure 5. Geometry of model fairings and their dimensions.

Figure 5 shows the shape of model fairings. In the case of Model-5, it is a quarter cylinder with the radius of h.

4. AERODYNAMIC PERFORMANCE ANALYSIS OF MODEL TRUCK

For analysis of the aerodynamic performance of the model truck on its running condition, the static pressure distribution on the surface of the vehicle has been analyzed. Drag and lift force has been calculated from the equations given below (Douglas *et al.*, 2001).

(1) Drag force (F_D) & its coefficient (C_D)

$$\sum F_D = \sum P_{par} A_{par} \sin \theta \quad (5)$$

$$\sum F_D = C_D \frac{1}{2} \rho_{air} \sum A_{x-dir} V^2 \quad (6)$$

$$C_D = \frac{2 \sum F_D}{\rho_{air} A_{x-dir} V^2} \quad (7)$$

(2) Lift force (F_L) & its coefficient (C_L)

$$\sum F_L = \sum P_{par} A_{par} \cos \theta \quad (8)$$

$$\sum F_L = C_L \frac{1}{2} \rho_{air} \sum A_{y-dir} V^2 \quad (9)$$

$$C_L = \frac{2 \sum F_L}{\rho_{air} A_{y-dir} V^2} \quad (10)$$

where

A_{x-dir}, A_{y-dir} : Areas of the model truck projected on y-z plane and x-z plane respectively; $A_{x-dir}=7.494 \text{ m}^2$, $A_{y-dir}=39.87 \text{ m}^2$.

P_{par}, A_{par} : Subscript, *par*, is for the region number of the vehicle surface divided into seven zones for integration of the pressure distribution (*par* = 1–7).

(3) Power saved by the reduced drag force with respect to Model-1 (standard model)

$$P_{sav} = (F_{D_{MOD-1}} - F_{D_{MOD-X}}) \times V_{car} \quad (11)$$

where

P_{sav} : Amount of brake power saved (Kw)

$F_{D_{MOD-1}}$: Total drag force (KN) of Model-1

$F_{D_{MOD-X}}$: Total drag force (KN) of the other model.

($X = 2-5$)

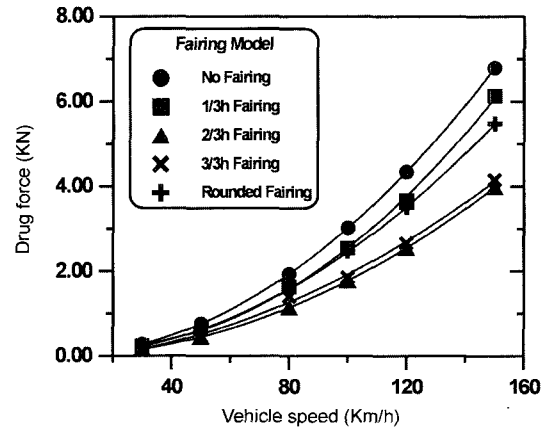
V_{car} : Speed of tractor-trailer (m/s)

5. RESULTS AND DISCUSSION

In this numerical study, an aerodynamic effect of a fairing system on a heavy-duty truck was examined. A side-wind may cause a driving stability problem of truck but such factor is not in the scope of current study and further study should be required on this matter. Thus, this study assumed that the model truck is running straight forward at a constant speed without an effect of side-wind.

Figure 6 shows variation of aerodynamic drag force on the fairing models with the change of vehicle speed.

The drag force increases with the velocity of vehicle in all models. However, it can be noted that the model truck with any kind of the fairing system has lower drag force

Figure 6. Variation of aerodynamic drag (F_D) force on different model of fairing system.

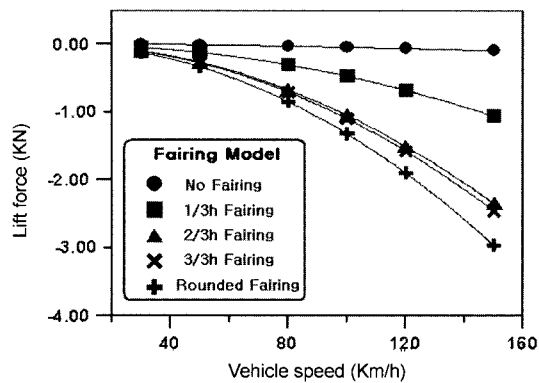


Figure 7. Variation of aerodynamic lift (or downward) force (F_L) on different model of fairing system.

than the standard truck without fairing system in all speed ranges. Generally, it is known that a rounded shape of fairing (Model-5) has good aerodynamic effect to reduce the drag on the immersed body. However the model truck with 2/3h and 3/3h fairing have lower drag forces than the truck with the rounded model fairing in all speed ranges. The truck with 2/3h fairing, has the lowest drag force of all in all speed ranges.

Figure 7 shows variation of aerodynamic uplifting or downward force generated on the model trucks with the change of vehicle speed. Appropriate downward force generated on a running vehicle keeps the body steadily on the road surface and the force contributes to increase the driving stability of the vehicle. However, if the force is substantially higher than needed, the rate of fuel consumption will be increased due to the increased rolling resistance on road.

Figure 7 shows that the negative uplifting or downward force increases with the higher fairing system in all speed ranges. It is due to that airflow passes over the topside of the model truck is smaller for higher fairing system. Therefore, the air speed gets slower and the static pressure distribution on the upper body increases and the downward force increases relatively.

In Figure 8, it is shown that the model truck with any

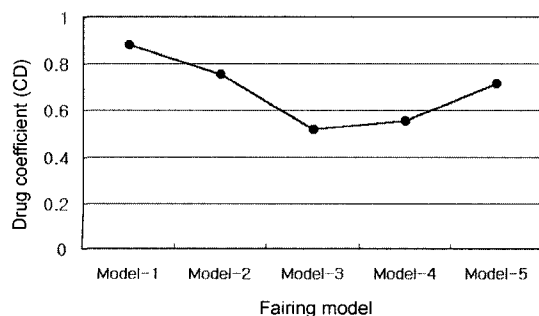


Figure 8. Drag coefficient (C_D) of each fairing model.

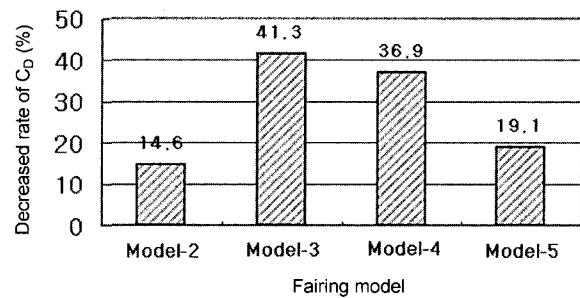


Figure 9. Decreased rate of drag coefficient (C_D) for each model fairing with respect to Model-1.

fairing system have smaller drag coefficient (C_D) than the non-fairing system truck (Model-1). The truck with Model-3 has the smallest drag coefficient of all. The rounded fairing truck with Model-5 has bigger drag coefficient (C_D) than the truck with the flat type model (Model-4) even though both of the fairing models have same size in height (3/3h). In general, the rounded shape object seems better than the flat type one in flow resistance characteristics. However it is found that curvature of rounded fairing is very important design factor to be considered to minimize the flow resistance on an immersed body.

Figure 9 shows the percentage reduction of drag coefficient of the model trucks with fairing system compare to the standard truck without fairing system. It can be seen that the reduction of drag coefficient is substantially high for trucks equipped fairing system than that of non-fairing system. The best fairing system is Model-3 which reduced the drag coefficient (C_D) 41.3%. Therefore, it can be concluded that the suitability of fairing system depends upon the configuration of a heavy-duty truck at its given traveling condition.

In Figure 10, it should be noted that when the negative lift coefficient is unnecessarily higher, the rate of fuel consumption of a truck increases more than it required which is due to the increased rolling resistance As would

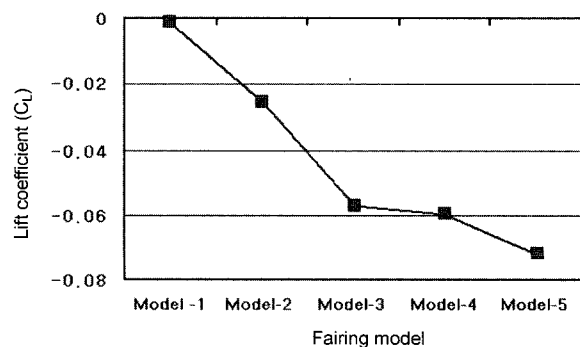


Figure 10. Lift coefficient (C_L) of each fairing model.

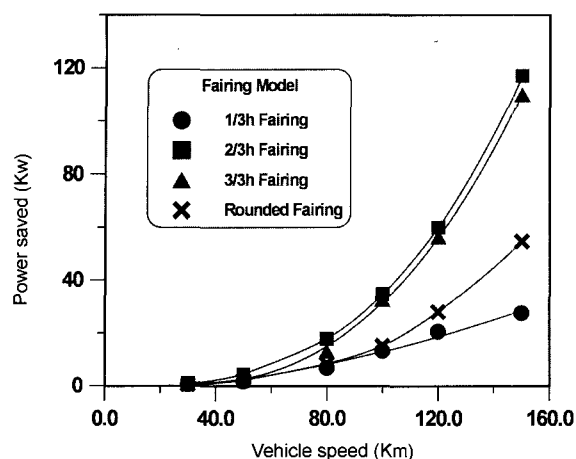


Figure 11. Variation of brake power (Kw) saved by drag reduction on the different fairing model.

Table 2. Engine brake power saved by drag reduction.

	30	50	80	100	120	150 Km/h
Model-2	0.4	1.6	6.7	13.1	22.5	27.5
Model-3	0.9	4.3	17.7	34.6	59.9	117.0
Model-4	0.9	4.0	11.9	32.5	56.2	109.8
Model-5	0.4	2.0	8.3	15.1	28.0	54.6

(Unit: Kw)

be expected, the standard truck without fairing system has the smallest value of the negative lift coefficient among the models. The downward force generated by a running vehicle is increased as the installed fairing system is higher.

Figure 11 shows engine brake power saved by the fairing system installed on the model truck. As shown in the figure, the higher vehicle speed is reached, the bigger of power saved is obtainable. Model-2 and -3 shows higher aerodynamic performance which contributes to engine power saving among four different models of the fairing system. General speaking, the average driving speed of tractor-trailer on a highway is ranged from 80 km/h to 100 km/h. The maximum amount of brake power of an engine saved on the truck by Model-3 is about 34.6 Kw at the speed of 100 Km/h. When a velocity of the heavy-duty truck is over 80 Km/h the drag force increases rapidly as shown in Figure 6. The brake power saved on an engine also increases quickly over the speed range of 100 Km/h.

6. CONCLUSIONS

From the numerical study, it was found that a roof-fairing system is very important device to minimize aerodynamic drag force on a running heavy-duty truck.

Because the pressure drag on the vehicle affects to the fuel consumption rate of it. Therefore, an optimum design of the drag reduction device for trucks is very important matter to study not only for the fuel economy in transportation industry but also for the environment protection problem. An aerodynamic down force produced on a running vehicle should also be carefully considered for an optimum design of fairing system, which may contribute to the increment of rolling resistance of the vehicle.

- (1) Model truck with any type of the fairing system has lower aerodynamic drag force than the standard truck with no-fairing system. However, a down force that related to the rolling resistance of a running vehicle may be increased at the same time. It indicates that the design of a fairing system depends on the configuration of a heavy-duty truck and its traveling condition.
- (2) Model-3 with 2/3h in height has the lowest aerodynamic drag force among the fairing models. It means that Model-3 induces lower boundary layer thickness at the top leading edge of the container, which contributes lower turbulent kinetic energy at the rear side of the truck that can affects the aerodynamic drag force on the truck.
- (3) A rolling resistance of the truck on road is results of the the down. It shows that the model truck with a fairing system has bigger downward force than that of the non-fairing system, and the higher the fairing system is, the bigger the down force is generated.
- (4) The rounded fairing system (Model-5) has bigger drag and downward forces than that of the model-4 in all speed ranges even though these models have the same height. From this result, it can not be concluded that the rounded shape has better aerodynamic performance than that of the flat type. Therefore, it can be noted that the height and curvature radius of the surface of rounded fairing model is important design factor to get the optimized configuration of a rounded fairing model.

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