

# Investigating the Impact of Train Shape on the Aerodynamics Performance of Medium-Speed Trains

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## Abstract

A number of studies have discussed the advantages and disadvantages of aerodynamics in developing the body design of a train. The purpose of this paper is to examine the effect of the shape of tail and nose of the train on the aerodynamic performance (drag force, lift force, and noise) of the medium-speed train (120 -150 Km/hour). The literature study in this paper was 3D CAD design, ergonomic environment comprehension, aerodynamics, and train body model. There were three types of models tested, namely the train models in Indonesia at hand, R-R model, and R-S model. Whereas, CAD software, Computational Fluid Dynamics (CFD), and Computational Aero-acoustics (CAA) were used to answer the problems found in the study. Based on the results of the test, it is found that the available train models are not feasible for medium-speed trains with an average Cd value as much as 0.972, an average drag force by 6515.8 N, and an average lift force that is equal to 19401 N. The high value of lift force is dangerous for train stability. Therefore, it can be concluded that based on the results of the initial simulation, the train shapes developed at medium speed are the R-S model and the S-S model.

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## I. RESEARCH BACKGROUND

The train is a very beneficial means of mass transportation that is used to reduce the density of traffic on the highway, especially for highly populated countries. In general, there are several benefits gained from a train as public transportation, including moving the people's economy, safety, fuel saving, reducing pollution, reducing traffic jam, increasing social sense for a disabled person/pregnant women/children/parents, and more free time. Robyn RM Gershon (2005) stated that mass transit is very dependent on government policy and the availability of its infrastructure. In improving train services, comfortable and safe design is one of the important factors that must be met. This is inseparable from the initial planning of the design and shape of the train and its relation to the aerodynamics level.

The aerodynamics of a train will have an impact on train stability, fuel use, passenger comfort, the comfort of people passing around the train tracks, and the comfort of the residents around the train tracks. There has been a lot of research that investigated the behavior of the wind on trains such as Stathopoulos 1997, 2002, 2006, Baker 2007, Mochida and Lun 2008, Blocken et al. 2011, Moonen et al. 2012, and Blocken 2014. As for an example, AdelyaKhayrullina (2015) used CFD simulation to examine the effects of wind from passenger trains which passed the tunnel. The threshold values for wind discomfort were selected based on the findings that wind speeds over 5 m/s can disturb the walking or sitting of the passengers (Lawson and Penwarden, 1975). Besides that, wind speeds of 2.4 to 5.5 m/s can mess the hair of the passengers, bother the reading on sheets of paper, and cause a dust disturbance. The difference in air pressure inside and outside

the wagon can make passenger uncomfortable (Baker, 2014).

The escalation of aerodynamic forces can affect train stability which then risks the train to be off track; this can be explained in simulations (Suf, M. Salleh, et al., 2017). The potential of energy saving by reducing the drag force of the train is very significant (B. Strom, 2008), (Ioan, Sebesan&Bogdan, Tarus, 2013). An earlier study which examined the aerodynamic barriers to coal-carrying wagons showed that a 25% reduction in drag force was equal to a 5% fuel savings (Stodolsky, F., 2002). Based on the explanation above, there are several factors that will be investigated to determine the right design for medium-speed trains, namely aero-acoustics (vorticity), drag force, lift ratio, and pressure distribution.

## 2. MATERIAL & RESEARCH METHODOLOGY

### 2.1. Aerodynamics

NASA defines aerodynamics as the way the air moves around objects. The word comes from two Greek words: *aerios*, that is in concern with air and *dynamic* which means strength. Aerodynamics is the study of the strength and motion of objects produced by air. There are two basic parameters that describe the fluid flow above the object of a train: Reynolds (Re) and viscosity ( $\mu$ ) in Equation 1. Reynolds number shows the transition between two current boundary layer conditions. The behavior of the fluid layer is strongly influenced by the pressure that varies along the direction of the flow. The relationship factors of the fluid in the boundary layer flow on top of small plates can be described in the equation below(John D., 1995).

$$Re = \frac{\rho VL}{\mu}$$

.....Equation1

Technically, the aerodynamic barriers of a train design are divided into two categories, namely: drag coefficient (Cd) and lift force (Fl).

#### 1.) Drag coefficient (Cd)

The drag coefficient is the horizontal aerodynamic drag which depends on the parameters of fluid density ( $\rho$ ), the speed of the fluid to reach the train body (V), and the frontal area of train design (A). The ideal train body design aims to produce the lowest drag coefficient while producing the high acceleration and great fuel economy. The equation of the drag coefficient is shown in Equation 3 and it is a non-dimensional parameter (Banard, R.H.,2001)

$$Cd = \frac{2Fd}{\rho V^2 A}$$

.....Equation2

Where:

Cd = drag force coefficient

Fd = Drag force (N)

V = speed of air relative to car (m/s)

$\rho$  = density of air (Kg/m<sup>3</sup>)

A = frontal area of the vehicle (m<sup>2</sup>)

#### 2.) Lift force (Fl)

The lift force (Fl) parameter is used to investigate the effect of aerodynamics on the weight of a train. This will change the fuel consumption and stability of the train body. A very high FL value will disturb the stability of the train body while a very low FL value will require more fuel consumption. The combination of stability, speed, and the need for fuel is the meeting point in determining the amount of FL that must be presented in the aerodynamic test of the train body. The following Formulation 4 explains how the FL value is built by the flow of the fluid through the train body.

$$FL = \frac{1}{2} \rho V^2 A$$

C<sub>L</sub>.....Equation 3

Where;

C<sub>L</sub> = Lift Force coefficient

#### 3. Aero-acoustics

The Lighthill-Curle equation (Equation 5) is applied to evaluate turbulent wind noise at low Mach numbers ( $M \ll 1$ ). The Lighthill-Curle equation is based on the Navier-Stokes equation with a combination of mass, energy, and conservation of momentum. The pressure

fluctuations for air flow will build up waves and turbulent sounds as explained by the vortex configuration. The Ffowcs William Hawkings (FW-H) acoustic model in ANSYS Fluent is used to convert the time of fluctuating pressure to a sound signal (5)(Broch J. T.,2002)

$$(\rho - \rho_0)H(f) = \frac{\delta^2}{\delta x_i \delta x_j} \int_{v(\tau)} \frac{[T_{ij}]}{4\pi c_0^2 |x-y|} d^3 y$$

$$- \frac{\delta}{\delta x_i} \int_s \left[ \frac{\rho v_i v_j - V_{jj} + (p - p_0)(\delta_{ij} - \sigma_{ij})}{4\pi c_0^2 |x-y|} \right] dS_{j(\tau)}$$

$$+ \frac{\delta}{\delta x_i} \int_{s(\tau)} \left[ \frac{\rho v_j}{4\pi c_0^2 |x-y|} \right] dS_{j(\tau)}$$

.....  
.Equation 4

## 2.2. Train Design

A train is a form of mass transportation consisting of a series of connected vehicles that generally run along the train tracks to transport cargo or passengers. The motion power for a train is provided by separate locomotives or individual motors in several self-propelled units. Although dominated by steam power, the most common types of locomotives are diesel and electric. Based on the distance traveled, trains are divided into several categories such as long-distance trains, short-distance trains, and within cities. Long-distance trains consist of high-speed rail, inter-city trains, regional trains, and higher-speed rail. Whereas, short-distance trains are usually known as commuter trains. On the other hand, within cities trains consists of rapid transit, tram, light rail, monorail, and maglev.

The rails or train tracks are usually installed on a road covered with pebbles or ballast. The ballast functions to reduce vibration and bending due to the weight of the train. To cross the bridge, wooden bearings are used because they are more elastic than concrete pads. There are several gauges used; the wider it is, the more stable the rails so that the higher the speed of the train. The track widths (gauge) which are commonly used include:

- 1000 mm: used in Malaysia, also known as “meter gauge”.

- 1067 mm (3 feet 6 inches): generally used in Indonesia, also known as “narrow gauge”. Narrow gauge is suitable for mountainous areas because wide tracks require larger costs and the construction itself is more difficult.
- 1435 mm (4 feet 8.5 inches): widely used in the world so that it is also called as “standard gauge”.

A train consists of 3 main parts, namely the head (locomotive), the body (wagon), and the tail. Kai Cui et al. (2012) tested the aerodynamic effect on the shape of the nose and tail of the train into two types namely Rocket (R) and Sword (S) for a high-speed train with varying slenderness ratios. The best choice for the train is the combination of R-S head and tail model with 8.3 slenderness ratio and the combination of S-S model with 8 slenderness ratio. Figure 1 is the existing model of the train locomotive in Indonesia. Tian (2006) pointed out that the extension of the train head to become more slender can effectively improve the aerodynamic performance. Chen (1998) assessed the drag force characteristics in tunnels and revealed that there is an effect of head slenderness ratio on aerodynamic resistance when the wind speed has reached 50 m/s. In general, train wagons have 12.5m length, 2.64m height, and 2.605m width (Sarnia O. &Yusnita R., 2015).



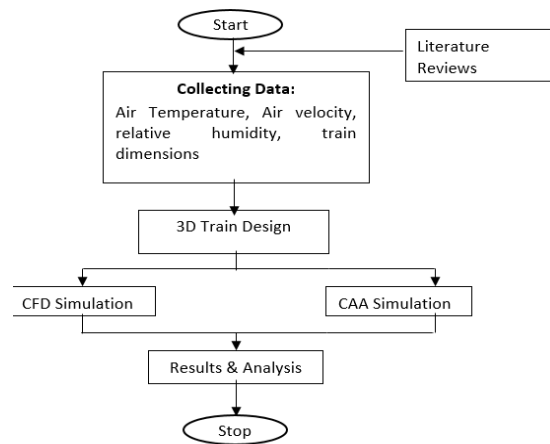
**Figure 1.**The shape of the train locomotive in Indonesia (PT. KAI, 2019)

### 2.3. Research Methodology

To answer the question about the effect of soil profile on the train track towards the aerodynamic performance, a model test with simulation was applied. The model was built in the form of 3D models based on the current conditions and development concepts. The simulations with Computational Fluid Dynamics (CFD) were used to determine the value of drag force and drag coefficient, lift force, and pressure distribution around the head, wagon, and tail of the train. The method used was Detached Eddy Simulation (DES) with a mixed algorithm between the Reynolds-Averaging equation (RANS) and Large Eddy Simulation (LES). The DES algorithm has been described by Spalart (1997). Computational Aero-acoustics (CAA) simulation was used to obtain the source of noise and the amount in Db caused by vorticity of air passing through the train. While on the other hand, Finite Element Analysis (FEA) simulation was applied to measure the amount of vibration caused by the aerodynamics. The primary data collected were the measurement data of existing rail dimensions while the secondary data were the S and R train data size, the data of train track information, and the environmental data. Besides that, the data from environmental parameters of water temperature ( $^{\circ}\text{C}$ ), air velocity (m/s), and relative humidity (%) in tropical conditions were collected.

Figure 2 illustrates the details of the research stages to simulate the train aerodynamic and aero-acoustics. The first step was to collect data as initial information to design 3D CAD of the existing train models. In addition, the information on environmental conditions such as temperature, relative humidity, air speed, air direction, and air pressure was needed for the input on CFD simulation. After the train model was finished, the next step was to define the domain of constraint and boundary condition. The results of the CFD simulation will be used as the input from the simulation. In the final stage, a discussion process was done to deliver all the results from the simulation and discuss the aerodynamic performance of various

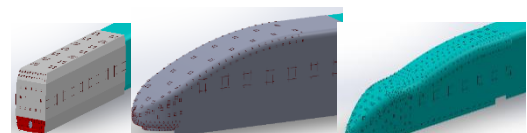
medium-speed train scenario models (120-150 Km/hour).



**Figure 2.** The flowchart of research steps for the best aerodynamic performance

### 3. RESULTS & DISCUSSION

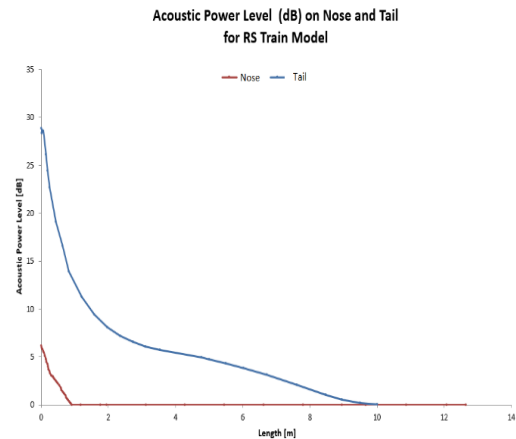
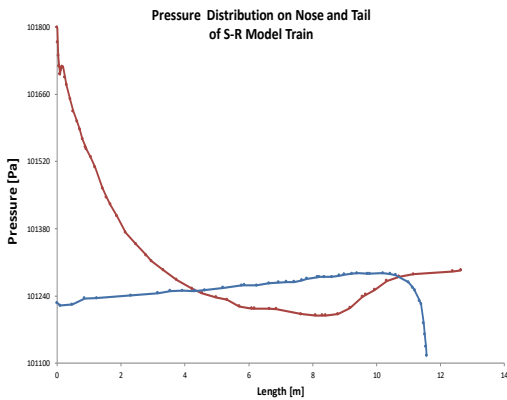
Based on the results of several references on high-speed trains, three forms of the nose and tail of the train were tested in this study. From the information gathered, there are two recommendations for the main model such as R-S model (the nose of the locomotive is in a rocket shape and the tail is in the shape of a sword) and S-S model (the nose of the locomotive and the wagon tail is in the form of a sword). In addition, this study also simulates aerodynamics performance for the existing train models in Indonesia. The description of 3D models that have been simplified can be seen in Figure 3 below. According to the methodology described, 3D models are the main basis for simulating aerodynamics performance.



**Figure 3.** 3D CAD simplification for the existing train models, R-S model, and S-S model

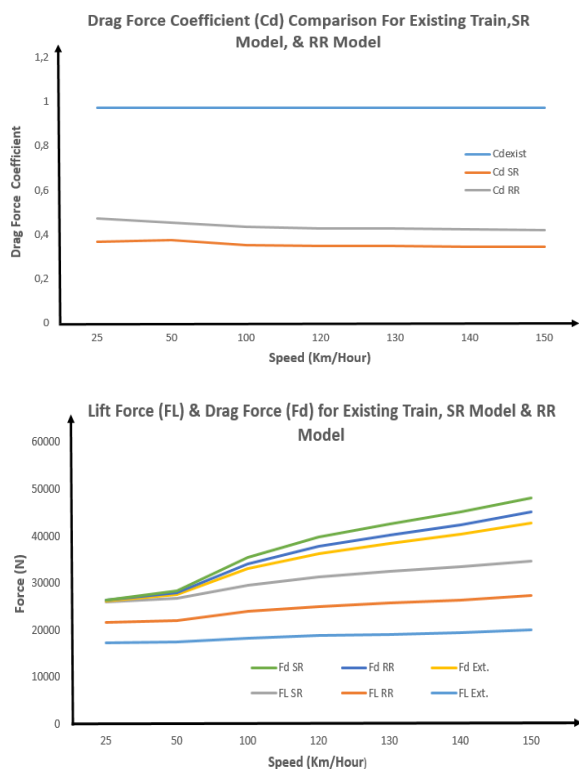
Figure 4 shows the pressure and noise distribution generated by the air flow passing the train with maximum speed in medium-speed train (150 Km/hour). In the first picture, the red

line points out the pressure distribution on the nose of the locomotive and the blue color describes the pressure distribution on the tail. The pressure at the tip of the nose receives a very large pressure which is around 101,800 pa and then decreases slightly until the lowest point at the end of the locomotive with a surface pressure by 101,240 pa. Moreover, the blue color demonstrates the air pressure distribution on the sword tail with a value that is slightly greater than 101,240 pa. The pressure variation in the tail tends to be smaller than what happens at the nose of the train. Next, in the second picture, the noise distribution caused by the air moving through the locomotive nose and tail is shown. The blue line illustrates the amount of noise that occurs at the nose of the locomotive and the red represents the noise on the train tail. From the graph, it can be assumed that at the end of the nose locomotive, the highest noise around 6 dB is produced. As for the train tail, a high noise value occurs behind the tail with a value of 28 dB due to the turbulence with high vortex value which then decreases at a distance of 4 meters from the back of the train tail.



**Figure 4.** The distribution of pressure and sound pressure levels (SPL) through the nose and tail of the train for R-S models with a speed of 150 Km/hour.

Figure 5 displays the differences in aerodynamic performance ( $C_d$ ,  $F_L$ ,  $F_d$ ) that occur in three train models (existing models, S-R model, and S-S model) that operate at medium speed 120 Km/hour to 150 Km/hour. The average drag coefficient value for the existing model is 0.972 with an average drag force by 6515.8 N and average lift force by 1940.1 N. Meanwhile, the drag coefficient value of R-S model is equal to 0.355 with the average drag force of 1970.4 N and average lift force of 6778.8 N. As for the S-S train model, the average drag coefficient value is 0.437 with average drag force of 2462.8 N and average lift force of 8976.9 N. Based on the comparison of  $C_d$  values that is done at medium speed (120 Km/hour to 150 Km/hour) for the three models, it is necessary to modify the existing model of the nose locomotive and tail of the train. The changes are not much different from the high-speed train that the R-S model and S-S model have a slenderness ratio by 8.3 and 8.0. Therefore, this model is a reference for future research and for the development of optimal shape and dimensions of the nose and tail of the train. In addition to that, the small lift force at medium speed in both models is very safe for stabilization and is better than the existing model.



**Figure 5.** The impact of different train models on Drag Force Coefficient ( $C_d$ ), Lift Force ( $F_L$ ) and Drag Force ( $F_d$ )

#### 4. CONCLUSIONS

This paper is able to show a significant difference in the aerodynamic performance (drag force coefficient, lift force, drag force, and aerodynamic noise) of the existing train model in Indonesia as well as R-S model and S-S model. The R-S model and S-S model have a very good aerodynamic performance to be run at high speeds because both of which have a slenderness ratio by 8.3 and 8.0 respectively. The two models also guarantee good stability in the wagon. This is indicated by a significant decrease in the lift force compared to the existing model. With a more slender shape, the trains produce a low turbulent intensity of air flow resulting in low noise. It is suggested for future research to find the optimal shape for the nose locomotive and train tail for R-S model and S-S model with 8.3 and 8.0 slenderness ratio at medium speed.

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