

The Impact of Design, Position and Combination of Aerodynamic Devices on Drag and Fuel Consumption

Marius-Dorin Surcel and Mithun Shetty
FPInnovations

ABSTRACT

The performance of several aerodynamic technologies and approaches, such as trailer skirts, trailer boat tails, gap reduction, was evaluated using track testing, model wind tunnel testing, and CFD simulation, in order to assess the influence of the design, position and combination of various aerodynamic devices.

The track test procedure followed the SAE J1321 SAE Fuel Consumption Test Procedure - Type II. Scale model wind tunnel tests were conducted to have direct performance comparisons among several possible configurations. The wind tunnel tests were conducted on a 1/8 scale model of a tractor in combination with a 53-foot semi-trailer.

Among others, the wind tunnel tests and CFD simulations confirmed the influences of trailer skirts' length observed during the track tests and that the wider skirt closer to the ground offer better results.

The differences in the shape, dimensions and position of rear deflectors and trailer skirts on the trailer are reflected in the test results. Track testing and CFD simulation confirmed that the approach to reduce the tractor-trailer gap can result in improved fuel efficiency.

The tests showed that combinations of aerodynamic devices can bring additional benefits. The results obtained by combining trailer skirts and trailer rear deflectors are better than those obtained by the trailer skirts or gap deflector alone. This can be explained by the additional reduction in aerodynamic drag at the rear of the trailer, or in the gap between the tractor and trailer.

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INTRODUCTION

Class 8 trucks consume approximately 68% of all fuel used by commercial trucks, from which about 70% is consumed by on-highway trucks [1]. Air resistance, after gross vehicle weight, is the largest factor responsible for vehicle energy loss and has an important influence on fuel consumption. The magnitude of aerodynamic drag is affected by the vehicle's shape, frontal area, and travel speed. From the energy necessary to sustain vehicle speed at 105 km/h, aerodynamic drag accounts for approximately 50% [2] and [3], and reducing aerodynamic drag by 25% results in a 10 to 15% fuel savings [1].

Figure 1 presents the power demand on a level asphalt road for a tandem drive tractor and a van semi-trailer combination with a gross vehicle weight of 40 tonnes, for two vehicle speeds, 100 and 120 km/h.

This diagram was obtained using a simulation tool based on mathematical models. Figure 1 shows that a decrease in vehicle speed from 120 to 100 km/h translates into a 19% decrease in fuel consumption and a 32% decrease in power demand.

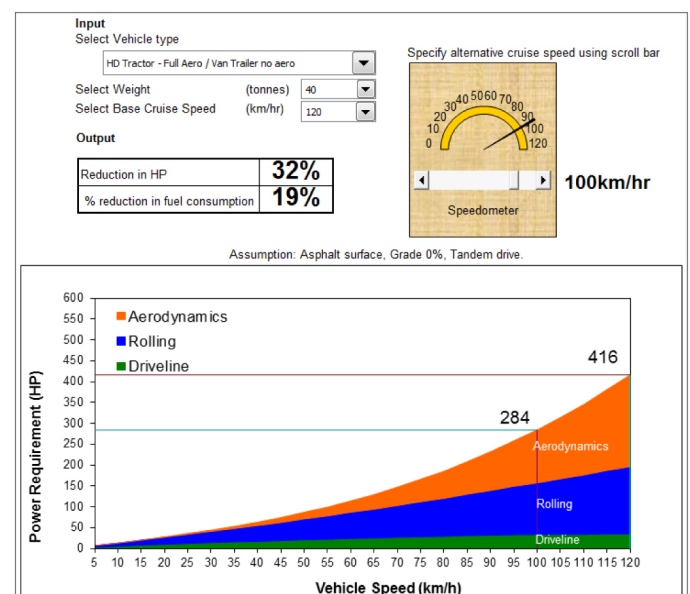


Figure 1. Speed impact on power demand and fuel consumption

TEST METHODOLOGY

Fuel Consumption Tests

Test Procedure

Testing took place at Transport Canada's Motor Vehicle Test Centre (MVTC) in Blainville, Quebec, which is operated by PMG Technologies. The fuel consumption tests were performed on the high-speed test track (BRAVO) [4]. The track is a high-banked, parabolic oval with a length of 6.4 km (4 miles). Figure 2 presents the test site.

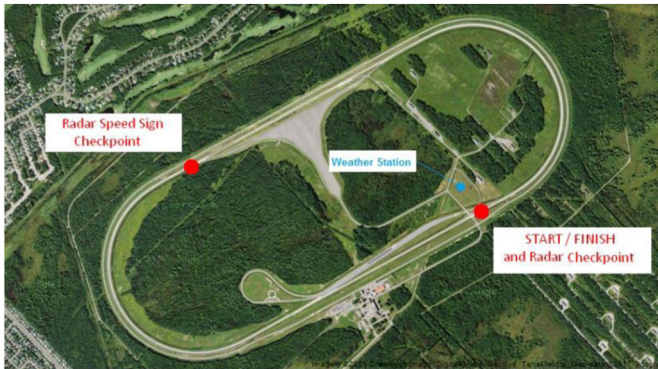


Figure 2. Map of test track with radar checkpoints and weather station location.

The tests were conducted according to the SAE J1321 Fuel Consumption Test Procedure - Type II [5]: the test compared the fuel consumption of a test vehicle operating under two conditions using an unmodified control vehicle. Fuel consumption was measured by weighing portable tanks before and after each trip.

For each test, the control and test vehicles had the same general configuration and were coupled to the same semi-trailers for the base and test segments. The vehicle (tractor and semi-trailer) weights remained the same throughout the entire test period. The vehicles were in good working condition, with all settings adjusted to the manufacturers' specifications. Standard tractor-trailer gap is 1.143 m (45 in.).

The test consisted of a baseline segment (using non-modified vehicles) followed by a final segment (the test vehicles were modified, while the control vehicle stayed in its original state). For both the baseline and final segments, the representative results were the ratio between the average fuel consumed by the test vehicle and the average fuel consumed by the control vehicle (the T/C ratio).

The nominal values for fuel savings and for fuel improvement were determined from the analysis of the measured fuel data, and reflect the changes resulting from the modification being tested on the test vehicle. These nominal values consisted of the percentage difference between the final ratio $(T/C)_f$ and baseline ratio $(T/C)_b$:

- Fuel savings:

$$F_s = 100 * \frac{(T/C)_b - (T/C)_f}{(T/C)_b} \quad (1)$$

- Fuel improvement

$$F_i = 100 * \frac{(T/C)_b - (T/C)_f}{(T/C)_f} \quad (2)$$

The result was expressed for the confidence interval of 95%, complying with the SAE J1321 Fuel Consumption Test Procedure - Type II [5], and determined from the variation in the measured fuel consumption data relative to the nominal value and the number of data values obtained.

Driving Procedure

Each day, before the start of testing, all vehicles were warmed up for the same amount of time (minimum one hour) at the test speed.

The drivers' influence on the results was minimized by conducting the tests on a closed circuit and by strictly controlling the driving cycle as follows:

- A fixed idling time was used.
- Drivers started with maximum acceleration.
- Drivers maintained a constant driving speed using the cruise control.
- Drivers steered as close as possible to the painted line at the right side of the track, without touching it.
- After the established test duration was complete, drivers stopped using the cruise control at a designated point.
- During deceleration, drivers used only the service brakes and did not accelerate.
- Once at the end point, the trucks idled before turning the engine off. All the vehicles in a test run idled for the same duration runoff time.

The time interval between two consecutive trucks remained the same in order to avoid the effects of turbulence caused by other trucks and prevent multiple trucks from being present at the same place and time on the track. The driving cycle was controlled with two radars. A radar speed sign displayed the speed of oncoming vehicles using highly visible LEDs, and was checked by the test drivers at every lap. The other device was a radar gun, operated by the test personnel, and placed on the opposite side on the track. Drivers received instructions by two-way radio, to ensure that the speed of the vehicles and the distance between the vehicles on the track remained constant. The duration of the runs was also checked periodically. The vehicles were instrumented with global positioning system (GPS) units, which were used to check vehicle speed and distance.

Model Wind Tunnel Procedure

For the trailer skirts, the tests were conducted on a 1/8 scale model of a Navistar Prostar Sleeper tractor in combination with a Wabash 53-foot semi-trailer (Figure 3). Every detail of the full scale tractor/trailer that encountered wind was accurately modeled, and the model had articulating suspension and rotating wheels. The trailer-tractor gap and bogey position were adjustable. This model also included internal flow modeling from the tractor grill into the radiator and then into the engine bay. The tests consisted of two phases: setting the initial baseline, and component testing of various configurations. To set the baseline, a reference tractor trailer gap was used with a conventional bogey position [6]. Standard tractor-trailer gap is 1.143 m (45 in., i.e. 5 5/8 in. in the scale model). Aerodynamic characteristics are presented in Table 1.



Figure 3. Navistar Prostar Sleeper - Wabash 53-foot semi-trailer 1/8 scale model.

Table 1. Model aerodynamic characteristics.

Drag coefficient at 0° yaw angle and 105 km/h (60 mph)	C_D	0.557
Wind-averaged drag coefficient at 105 km/h (60 mph)	C_{DW}	0.598
Scaled frontal area, m ²	A	10.38

Because the tests were conducted on 1/8 scale model, an equivalent flow to the full scale model must be assured for a given full scale speed. A given flow condition is characterized by the Reynolds number (Re), which represents the ratio of inertial forces to viscous forces. Consequently, the model tunnel wind speed must give the same Reynolds as the full scale simulated test speed. Tests conducted by NASA on the Reynolds number necessary for an 1/8 scale tractor semi-trailer combination being simulated as a full scale truck running at 105 km/h (65 mph) shows that the tunnel testing speed of 180 km/h (111.8 mph) is within the acceptable Reynolds number range required for accurate comparisons to full scale trucks at 105 km/h [6].

The tests were conducted as per SAE J1252 standard [7] at 180 km/h sweeping the model through the following yaw angles: 0 deg; 9 deg; 6 deg; 3 deg; 0 deg; -3 deg; -6 deg; -9 deg; 0 deg. Preceding every

individual test run were two model tares. The first tare was a static tare weight, which removed the static weight of the model. The second tare was a rolling tare without wind completed at 180 km/h which removed any mechanical drag imparted through the rotating wheels. All aerodynamic forces were measured using an AEROTECH 6 component load cell balance. This balance provided three forces: Lift, Drag and Side force as well as three moments: Pitch, Roll and Yaw moments. The repeatability recorded during the baseline setting was under 0.25% for wind-averaged drag coefficient.

CFD Simulation

For this study, Ansys CFD-Flo commercially-available software was used [8]. The problem was solved on a Dell Precision T3500 Workstation that had 12 GB of RAM (1333MHz, DDR3 SDRAM, ECC-3 DIMMS) on a Quad Core Intel processor (Xeon® W3565 3.20GHz, 8M L3, 4.8GT/s) and a 64 bit Windows® Window 7 operating system with one core Ansys Solver license. The full scale simplified tractor-trailer model used in this study is presented in Figure 4. The width of tractor and trailer are 2.4 m and 2.6 m respectively. To simplify the grid requirements, the trailer mud flaps, landing gear and end guard rail were not modeled, and dual tires were modeled as single wide tires. The tractor model was simplified as the change in flow between the tractor and trailer gap, and the change of flow in the undercarriage were subjects of interest. The CFD model in this study was used to compare the change in drag with wind tunnel and track test results. The absolute drag values cannot be compared due to the difference in model and test conditions. The domain size illustrated in Figure 5 meets the SAE J2966's minimum domain size requirement [9]. For a reasonable estimate of change in drag, a suitable grid, turbulence model and order of discretization were chosen, and drag force convergence was monitored. A tetrahedral mesh with a fine mesh size was used around the body as shown in Figure 6. The same mesh setting was used for the baseline and treated simulation runs. Table 2 presents the input set-up parameters for CFD models. The Shear Stress Transport turbulence model with wall treatment features was used to resolve the flow separation around the body [10].

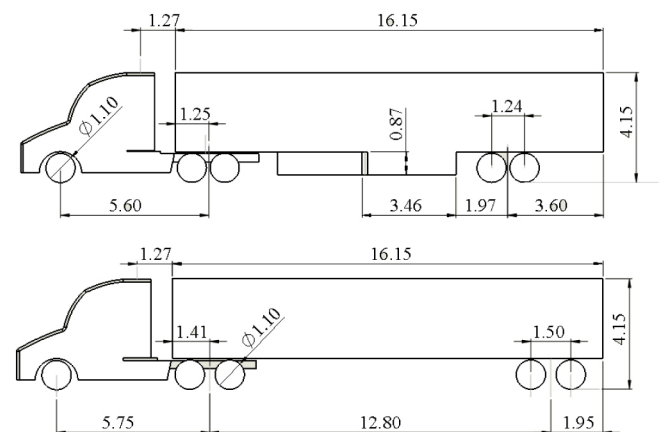


Figure 4. Truck Dimensions (top: baseline for skirt simulation, bottom: baseline for gap simulation; dimensions in meters)