J. Wind Eng. Ind. Aerodyn. 147 (2015) 262–272

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

From lab to full scale Active Flow Control drag reduction: How to bridge the gap?

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ARTICLE INFO

Keywords:
Drag reduction
Fuel consumption
Active flow control
Truck trailer aerodynamics

ABSTRACT

Active Flow Control (AFC) is being investigated as a tool for boundary layer separation delay. Increasing lift by delaying stall has been the most common objective. More recently AFC is also being studied for drag reduction and mitigation of unsteadiness, resulting from massively separated flows. As such, fuel savings of heavy ground vehicles, while challenging, is a worthy task due to the huge economic, environmental and political impact. This paper describes a series of experiments aimed at increasing the base pressure on the trailer-end of a large truck–trailer configuration driving at highway speeds. In parallel to fundamental studies, not reviewed here for brevity, two road test campaigns were completed; a half scale wind tunnel test and smaller scale generic vehicle model wind tunnel experiments are described and analyzed. The method currently uses a 1/4 cylinder shaped rear-end mounted add-on device in which an array of synchronized Suction and Oscillatory blowing (SaOB) actuators is mounted. The passive as well as active effects of the steady suction and unsteady sideways-oscillating blowing are documented and careful experimentation allows the energy budget to be directly calculated from wind tunnel experiments. Good agreement between road tests and scaled tunnel model tests was found on the path to product development.

1. Introduction

The US transportation sector is responsible for 28% of the Greenhouse gas emissions in 2012.[1] Of this part, the heavy ground transportation sector is the 2nd largest fossil fuel user (22%) after the light vehicles sector (59%) and is close to three times larger than the air transportation sector (8%).[2] Millions of heavy truck–trailer vehicles travel on the highways daily[3,4] and consume between 0.5 and 2.0 l/km each.[3]

The contaminants production and effect on global warming are devastating.[1] The importance of the subject at hand provides motivation to the intensive research, the series of world meetings (McCallen et al., 2004; McCallen and Browand, 2007; Dillmann, 2010; International Conference of Vehicles Aerodynamics, 2014) on the subject and multiple government incentives, activities and business initiatives.

A recent review of the state-of-the-art truck aerodynamic drag and the efforts to reduce the related fuel consumption at highway speeds can be found in the book summarizing the third conference of truck aerodynamics held in Potsdam, Germany at 2010 (Dillmann, 2010).

A more recent web posting by Salary (⟨http://energy.gov/sites/prod/files/2014/03/f13/vss006_salari_2013_o.pdf⟩) summarizes the US recent efforts to minimize fuel consumption in the trucking sector.

In the US, about 20% of the fossil fuel consumption is related to heavy trucks, where each 1% is equivalent to about 1 Billion liters per year, worth close to 1 Billion dollars, and is responsible for more than 2 million tons of CO_2 emissions. Note that there are about the same number of trucks in Europe; they indeed drive 10% slower and therefore use about 15% less fuel (assuming the Aerodynamics related fuel burn is half the total), but the cost of fuel in Europe is generally twice the US prices. In a related report (Ortega et al., 2013) it was mentioned that with treatment of the truck–trailer gap, the sides of the truck and positioning 1.22 m long base flaps it is possible to reduce the drag by $\Delta Cd \approx -0.175$ or about 26% from $Cd \approx 0.7$ of the reference truck–trailer combination. It should be noted that the EU does not allow such long trailer-end devices and that the European heavy truck drag coefficient is typically 0.5 (as will be shown later) and not 0.7 (Hucho,

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[1] ⟨http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html⟩.
[2] ⟨http://cta.ornl.gov/data/chapter2.shtml⟩.
[3] ⟨http://cta.ornl.gov/vtmarketreport/pdf/chapter3_heavy_trucks.pdf⟩.
[4] ⟨http://www.statista.com/statistics/247022/registration-of-trucks-in-europe/⟩.

http://dx.doi.org/10.1016/j.jweia.2015.09.012
0167-6105/

Fig. 1. The truck–trailer configurations that participated in the US (top) and EU (bottom) AFC road test campaigns. The AFC device and air supply system (under the rear of the trailer, Seifert et al., 2010) are attached.

2002) making the EU potential drag reduction large but more difficult to achieve. The US market already offers a few trailer base devices claiming 5% fuel savings at highway speeds and hoping to capture a few percent of the market share by the end of 2014.[5]

Many active methods have been and are being studied to reduce the trailer base related pressure-drag using shorter devices than those allowed in the US, due to functionality considerations (El-Alti et al., 2010). Most notably is the effort to use super circulation concepts developed for aerospace applications on rounded rear-end add-on devices [e.g., Englar (2004, 2005)]. However, the energetic efficiency of such method is quite low, as noted in (Seifert et al., 1996) compared to unsteady AFC methods for boundary layer separation control. Indeed, applying the tangential wall-jet blowing concept to heavy truck–trailer configuration did not reduce the fuel consumption or even the aerodynamic drag (Kehs et al., 2010).

Since its introduction to the flow control community in 2003, fluidic oscillators became very popular flow control tool. The Suction and Oscillatory Blowing (SaOB) actuator (Arwatz, 2008a, 2008b) is extensively studied and has been used in several projects. Other groups worldwide use oscillators for separation control. It has been proposed to use this actuator for trucks drag reduction using an add-on device and encouraging results have already been presented in 2007 (Seifert et al., 2007, 2008). In 2010, first road test results were published (Seifert et al., 2010). The road test results were quite encouraging from an aerodynamic perspective and resulted in 5% fuel savings; however, the system was not energy efficient due to the poor design and choice of components of the air supply system, that was a low priority at the time. It was later found that the number of actuators used was conservatively high and could possibly be reduced by a factor of 2–3 (Shtendel and Seifert, 2014).

An additional series of road tests were conducted in Europe, following a few minor improvements to the AFC system. Following the test campaign conducted on a different type of truck, and the inconclusive nature of the fuel saving results, a collaborative wind tunnel study with Volvo Trucks Inc. was performed on a 1/2 scale model in which also the boundary layers on the trailer were measured. A methodical process to advance the AFC system towards higher efficiency, similar to the study reported in Wilson et al. (2013) improved the flow-physics understanding while highlighted the need of more fundamental studies.

Finally and more recently, scaled simplified vehicle model tests are conducted where the overall system efficiency is the main criteria of success.

All these tests are analyzed here and from the results a state of the project and future directions emerge. The structure of the paper is as follows: In Section 2 we present the experimental set up, in Section 3 we present the results and discussion and finally conclusions are provided with an outlook to bring this technology to field application.

2. Description of the experiments

Results from three main experimental set-ups are described below. Details on those experiments are provide in this section.

The first experiment is a road test campaign conducted on a European standard truck–trailer configuration at the FORD Lomel proving ground, Belgium. Additional details on the U.S. Road tests, conducted earlier with the same flow control system can be found in Seifert et al. (2010).

The second experiment is a half-scale model test performed on a Volvo truck–trailer configuration at 50–100% full-scale Reynolds numbers including moving ground effect. The test was conducted at the 9 m low speed tunnel of NRC Ottawa, Canada.[6]

The 3rd test is a medium scale (1/6th scale base surface area) generic truck configuration test conducted at the IAI LSWT in Israel.

Sections 2.1–2.3 provide detailed description of the above mentioned experiments.

[5] ⟨http://www.atdynamics.com/⟩.

[6] ⟨http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/wind_tunnel/nine_metre.html⟩.