ASSESSING THE FUEL SAVINGS OF AERODYNAMIC TRAILER DEVICES IN REALISTIC CONDITIONS

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Abstract
Great difficulties occur in predicting realistic fuel savings due to aerodynamic devices in early design stages. This paper follows the development of an aerodynamic drag reduction device for trailers in increasingly realistic conditions. Initial steps include computational fluid dynamic simulations and wind tunnel tests on a simplified vehicle model. Subsequently full-scale tests are performed. The first tests were conducted on a closed test track, followed by public road tests of various durations. Throughout all these steps the aerodynamic savings are measured, in order to establish a relationship between the aerodynamic savings and the realism of the test. The track test showed that the tail delivers a saving of 1.22 l/100 km at a constant vehicle speed of 85 km/h. The first operational test included the driver influence, loading and traffic, and resulted in a saving of 1.13 l/100km. The second, longer operational test includes seasonal changes and resulted in savings of 0.98 l/100 km. These results indicate that more realistic conditions including a varying velocity profile, during the test generally lead to lower savings.

Keywords: Commercial vehicles, low emission transport, trailers, aerodynamic drag reduction device, realistic conditions

1. Introduction

Reducing the aerodynamic drag level of heavy duty vehicles, and more specifically of semi-trailers, contribute largely to improve the fuel economy and thus accompanied CO_2 emissions. As road transport is one of the major contributors in emissions the European Commission has announced several measures to reduce the exhaust of harmful gases. One of the measures is allowing extra vehicle length solely for aerodynamic drag reduction. New 'weight and dimensions'-regulations (2015) allow an additional length of 0.5m for a foldable rear-end drag reduction device.
An aerodynamic development team has several design tools available that leads to an aerodynamic drag reduction device. Typically, the development of aerodynamic devices starts with an analytical review of available results and literature. With the aid of numerical simulations (computational fluid dynamics, CFD) and (scaled) wind tunnel testing flow structures are identified and initial concepts are evaluated. A wind or yaw averaged drag coefficient is used to indicate the performance of the aerodynamic devices. Several very basic methodologies exist to convert changes in aerodynamic drag coefficient to potential fuel savings.
Frasquet and Indinger (2013) suggest the following relationship:

$$Fuel\ saving\ [\%]\ =\frac{\Delta C_D[\%]}{3.5} \tag{1}$$

Where ΔC_D is the percentage drag reduction at a certain yaw angle, and *Fuel saving* is the percentage reduction of the fuel usage due to the drag reduction. By using the wind averaged drag coefficient, equation (1) will provide the wind averaged fuel savings.
According to Van Raemdonck (2012), roughly 40% of all energy consumption of a heavy duty vehicle at highway speeds is due to aerodynamic resistance while driving at a constant speed of 85 km/h. Thus, if all other contributions stay constant, an aerodynamic gain has to be multiplied with 0.4 to obtain the gain in fuel savings. Or, written as a fraction as in equation (1) this becomes:

$$Fuel\ saving\ [\%]\ =\frac{\Delta C_D[\%]}{2.5} \tag{2}$$

The ICCT white paper on European heavy duty vehicles by Delgado et al. (2017) mentions an average return factor (the percent fuel consumption reduction per percent drag coefficient reduction) of 0.32 for long haul cycles. This can be expressed as:

$$Fuel\ saving\ [\%]\ =\frac{\Delta C_D[\%]}{3.125} \tag{3}$$

Expressing the fuel savings in terms of percentages hides the influence of several vehicle parameters as it is a result relative to a reference value. Vehicle weight, for instance, has a great effect on fuel economy and thus also the potential savings expressed in percentages. Therefore assessing potential savings in absolute values, i.e. liter per 100km, is more transparent.
Advanced vehicle models do exist or can be developed to calculate absolute fuel savings. An example is the Vehicle Energy Consumption TOol (VECTO), described by Fontaras et al. (2013). This tool, commissioned by the European Commission, uses a collection of inputs such as fuel consumption maps, gear ratios, tire rolling resistance and others to model the fuel consumption over a given duty cycle.

However, all these methodologies rely on general relations and ideal conditions, such as no traffic (either negative effects like traffic jams or positive effects like platooning), no wear and tear, no adverse weather conditions. Therefore it is still necessary to perform track tests and on-road tests for longer periods of time while developing aerodynamic drag reduction devices. This paper describes the development and validation of an aerodynamic trailer rear-end device, with focus on determining the performance of the aerodynamic device in absolute values [l/100km] in realistic conditions.

2. Rear-end Drag Reduction Devices

Tractor semi-trailer combinations are mainly used for long-haul transport on European highways and are the biggest polluter, Delgado et al.(2017). This vehicle type, especially its semi-trailer, is being considered in order to develop aerodynamic drag reduction devices. A well-known rear-end drag reduction device are boat tails, a rearward extension of the semi-trailer where the panels have a certain slant angle. Besides the slant angle, boat tail length is a defining parameter towards a maximized drag reduction. Coon and Visser (2004) indicate that longer tails with a length over 1.0m perform better, i.e. generate a higher drag coefficient reduction. Therefore a maximum extra length of only 0.5m, defined by European regulations (2013), is putting the aerodynamic designer to a real challenge delivering a solution that generates sufficient fuel savings but also operates easily during daily usage.

Key to developing an aerodynamic device is estimating savings in realistic conditions. In this paper, the development of a rear-end device is described. The application of different tools is described as well as their predicted savings. Comparing the savings of every tool with the degree of realism offers the opportunity to discover trends.

3. Numerical Simulations

The development of the aerodynamic tail was initiated by performing CFD calculations based on the requirements set by SAE J2966 (2013). Together with the Institut für Strömungsmechnik (ISM) of the Technische Universität Braunschweig calculations were performed. The software package TAU , as discussed by Schwamborn, D. et (2006) was used to perform Reynolds Averaged Numerical Simulations. A full-scale simplified European model was simulated at a speed of 85 km/h, leading to width based Reynolds number of $5.8\cdot10^6$. A k-ω-SST turbulence model was used on a hybrid mesh with $22\cdot10^6$ cells. No yaw angle was applied. These simulations allow the identification of first potential drag coefficient reductions and flow patterns, thereby providing insight on how to influence the flow.

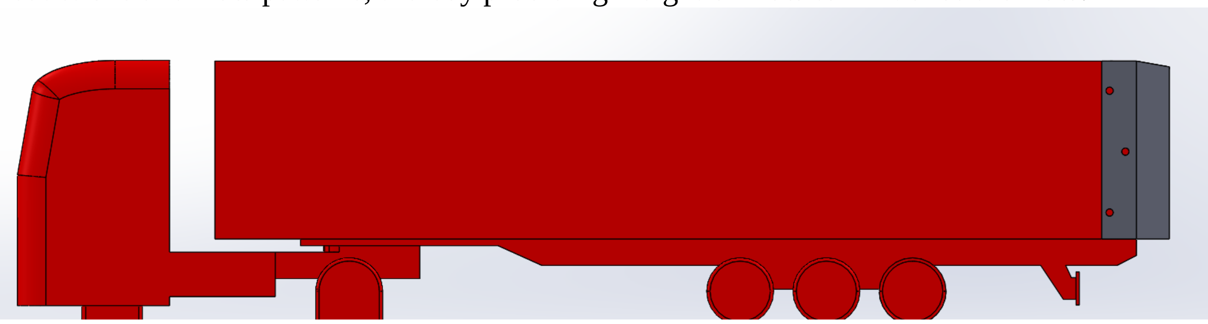

Figure 1 – CAD drawing of simplified vehicle model with tail

Several key parameters were researched, such as panel shape, top and side panel angle and panel length. A selection of results is shown in Table 1. This overview indicates what parameters were varied during the wind tunnel test, and what their effect on the drag saving is. The overlap is a portion of the tail that overlaps the side of the trailer, thereby ensuring a smooth transition to the angled portion of the tail. It was found that the design of this part, and especially the selection of the right height is crucial to achieving high savings. The best performing tail featured moderate slant angles and a small overlap, and provided a saving of 40 drag counts.

Table 1 - Overview of configurations simulated and the calculated drag coefficients.Symbolic values are used to represent commercially sensitive information.

Conf.	Panel profile	Overlap height [mm]	Side panel angle [°]	Top panel angle[°]	C_D [-]	ΔC_D [-]
1	-	-	-	-	0.506	-
2	Flat	-	α	ß	0.467	-0.039
3	Round	-	α	ß	0.468	-0.038
4	Flat	h	α	ß	0.469	-0.037
5	Flat	h	1.25 α	1.25 ß	0.472	-0.035
6	Flat	0.4h	α	ß	0.466	-0.040
7	Flat	0.4h	1.25 α	1.25 ß	0.470	-0.036

4. Wind Tunnel Experiments

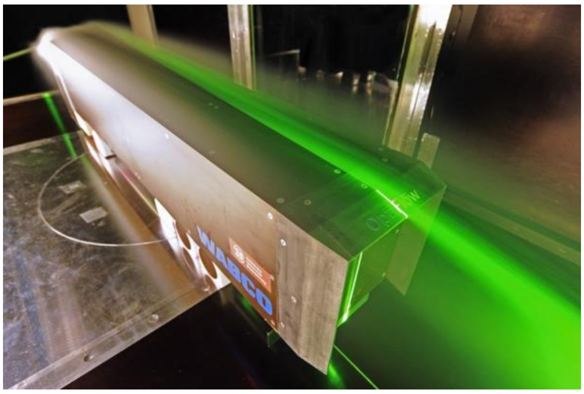

Figure 2 – Wind tunnel model.

The results of the numerical indicate initial potential aerodynamic drag coefficient reductions due to the application of a rear-end device. Next step is to perform wind tunnel experiments to validate the CFD results, add yaw dependent results and try a large number of tail variations in a short period of time to further improve the drag coefficient. The experiments were performed in collaboration with the ISM department of the TU Braunschweig. A low speed wind tunnel with a closed test section of 1,300 x 1,300 x 3,000 mm was used (width, height, length) The model was a simplified scale model (1:12) of European Heavy Duty Vehicle, with non-rotating tires, no engine simulation and no small details such as mirrors. The model did feature an integrated roof fender. The model was placed on an elevated ground board initiating a fresh thin ground boundary layer. The wind tunnel was operated at 55 m/s, leading to width based Reynolds number of $6.6 \cdot 10^5$. The used yaw angles were 0°, 3° and 7°. The wind averaged drag as defined by the SAE in J1252 (2012), was used to determine to assess the aerodynamic difference. A large number of models were tested with varying tail angles, tail configurations, panel shapes and overlaps.

From past experience, Van Raemdonck (2012), it is known that large slant angles can lead to problems with separation on the side panels in full scale. Therefore a rather conservative tail configuration with 0.83α top angle and ß side angle is chosen as the design to be validated with full-scale testing. This tail gave a wind averaged drag reduction of 46 drag counts, with a baseline model having a wind averaged drag coefficient of 0.464.

5. Track Testing

To assess the fuel savings of the selected aerodynamic device full-scale track tests are performed. This allows the determination of the actual fuel economy increase rather than drag reductions. Another benefit of track testing is that it includes realistic vehicles under realistic conditions such as the influence of real tires, transmission, engine performance, driver interaction, wind speed and direction.

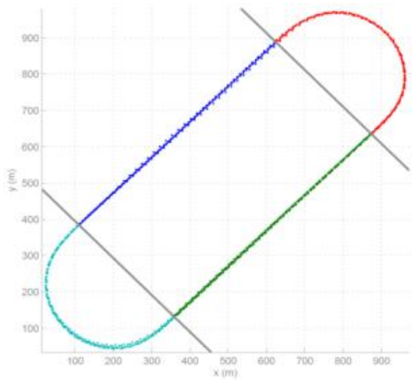

Figure 3 - Track segmentation

5.1 Test Location

The track tests were performed at the RDW test track in Lelystad, RDW (2016). This oval test track is 2.850 m long and features straights of 920m. The corners are banked allowing the vehicles to keep a constant speed of 85 km/h throughout the test.

5.2 Test Protocol

A modified SAE J1321 Type II (2013) protocol is used. A schematic representation of this protocol is shown in Figure 4. Two identical vehicle combinations, i.e. Control vehicle (CV) and the Test Vehicle (TV), are operated at the same constant driving speed, half a track apart. Both vehicles carry the same amount of loading. After a warming up phase, two sessions are performed. Each session consists of at least three runs of 10 laps. The first session is the baseline session, both vehicles will be identical, and will not be outfitted with any aerodynamic devices. The fuel consumption f in l/100km is recorded to determine the baseline difference between the two vehicles: $\Delta f_{baseline} = f_{TV_{baseline}} - f_{CV_{baseline}}$.

During the next Test session the aerodynamic device is deployed on the test vehicle, and again the fuel consumption of both vehicles is measured to determine the test difference between the two vehicles: $\Delta f_{test} = f_{TV_{test}} - f_{CV_{test}}$.
It is now possible to determine the difference due to the aerodynamic devices by subtracting the baseline difference from the test difference.

$$Fuel\ savings = \Delta f_{test} - \Delta f_{baseline} \quad (4)$$

By using this procedure it is possible to accurately determine the fuel savings of the aerodynamic rear-end device under realistic conditions.

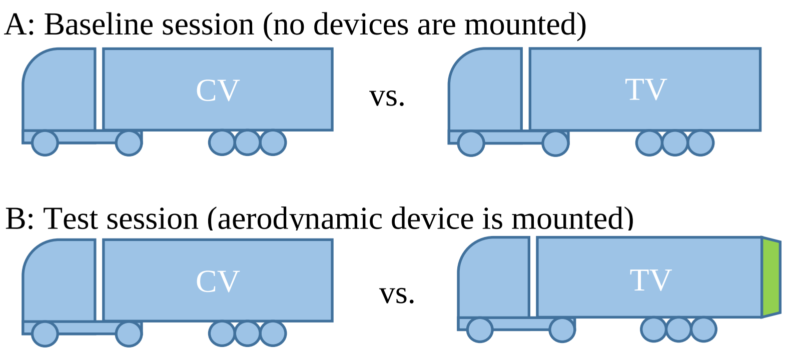

Figure 4 – Schematic representation of the J1321-II protocol

5.3 Data acquisition

This section discusses which types of data were collected during the test.

Vehicle Data

Two vehicle combinations were used, both of which were a SCANIA R416 EURO 6 pulling a 3 axle Krone Megaliner curtainsider without any cargo. The vehicle data (fuel rate, RPM, vehicle speed, etc.) was monitored from the CANbus using equipment developed by Squarell (Squarell 2018), shown in Figure 5. Additionally, GPS data was used to adjust the vehicle speed, and provide track segmentation and separation of the straights.

Figure 5 - Data acquisition system

Figure 6 - WindSonic system on vehicle

The on board wind speed and direction were measured 2 m above the vehicle using a WindSonic sensor, developed by Gill instruments (Gill 2016), shown in Figure 6.

Weather Data

The local weather conditions were also measured statically, at a 10m pole in the center of the track. The temperature was approximately 4° C in the morning, increasing towards 7° C in the afternoon. It was dry weather, and the track was dry throughout the test. During the test day there was in general a stronger than normal wind, with wind speeds averaging around 6 m/s. The wind was coming from the east, and as such, there was a head wind on the north straight and a tail wind on the south straight.

5.4 Results

The full-scale test results are shown in Table 2. One can clearly notice the sections with head wind and tail wind: a higher fuel economy on the north straight and a lower at the south straight. Additionally, the fuel savings due to the tail are much higher in head wind conditions. Furthermore, it can be seen that the Standard Error for the savings are an order of magnitude lower than the Delta's, providing confidence in the results.

Table 2 – Fuel consumption for the test session for the north and south straight, SE is defined as $\frac{\sigma}{\sqrt{n}}$, with σ representing the standard deviation, and n denoting the number of runs.

	North straight [l/100km]			South straight[l/100km]		
	CV	TV	Delta (±SE)	CV	TV	Delta (±SE)
Baseline	26.81	26.94	0.13 ±0.03	19.32	19.18	-0.14 ±0.05
Morning test	26.98	25.49	1.63 ±0.07	19.07	18.30	0.63 ±0.15
Afternoon test	26.36	24.74	1.76 ±0.18	19.36	18.38	0.83 ±0.09
Average test	26.67	25.12	1.70 ±0.12	19.22	18.34	0.73 ±0.12

6. Public Road Testing

Two different types of public road testing are performed, one day tests and operational tests. One day tests are similar in setup to the track tests. Again the modified SAE J1321 protocol is used, with two identical vehicles with identical loading driving at the same speed.. The second is the operational test, where the testing was incorporated in the daily usage of the vehicles.

6.1 One Day Test

A one day test was performed in cooperation with a Belgium fleet. A Saturday, was selected to minimize the interference of other vehicles and chances of a traffic jam. During this test two vehicles were operated at 90 km/h on the public highway E10 between Antwerp and Brussels. This stretch of 25 km was repeated 9 times. The two combinations used were Mercedes Actros 1945 Bluetec 6 pulling Krone curtain siders. The tractors were identical, whereas the trailers had the spare wheel at a different location. The Test vehicle had it at the pallet box location, whereas the control vehicle had the spare wheel at the end. For the first part of the day, the Tail was folded, and both vehicles were identical. Both vehicles were driving at the same time, separated by a distance of 5 minutes. In the morning the baseline runs are conducted while the afternoon was dedicated to the test runs. During this test the conditions were dry and there was an average wind of 3.6 m/s (lower than yearly average) , which was roughly aligned with the trajectory. The obtained fuel consumptions are displayed in Table 3 together with the fuel saving: a fuel economy increase of 1.5 l/100km is measured.

Table 3– Overview of fuel consumptions during One day test

	CV [l/100km]	TV [l/100km]	Difference [l/100km]
Baseline	19.1	20.0	-0.9
Test	19.4	18.8	0.6
Fuel saving			1.5

6.2 Operational Tests

Operational tests are similar to the one day test, with a baseline part (with no aerodynamic device deployed) and a test part with aerodynamic device deployed. Two operational tests were performed. One in cooperation with the same Belgian fleet for a duration of two weeks, and a second in cooperation with a Dutch fleet, for a duration of 35 weeks

Operational Test 1

The first operational test was a continuation of the one day test and had a duration of 8 working days, two vehicles were operated in Belgium and France, see Figure 7.

Figure 7 – Routes driven by vehicles during Operational test 1

Due to operational concerns, it was not possible to always have the same loading in both vehicles, on average the test vehicle was 0.25 tons heavier. Additionally, contrary to the one day test and the track testing, it was not possible to drive at a constant high speed. All speeds are considered for the determination of the fuel savings, and 75% of the distance was driven at more than 80 km/h. For alternating days, the tail of test vehicle was deployed (test part) or folded shut (baseline part). The results are shown in Figure 8.

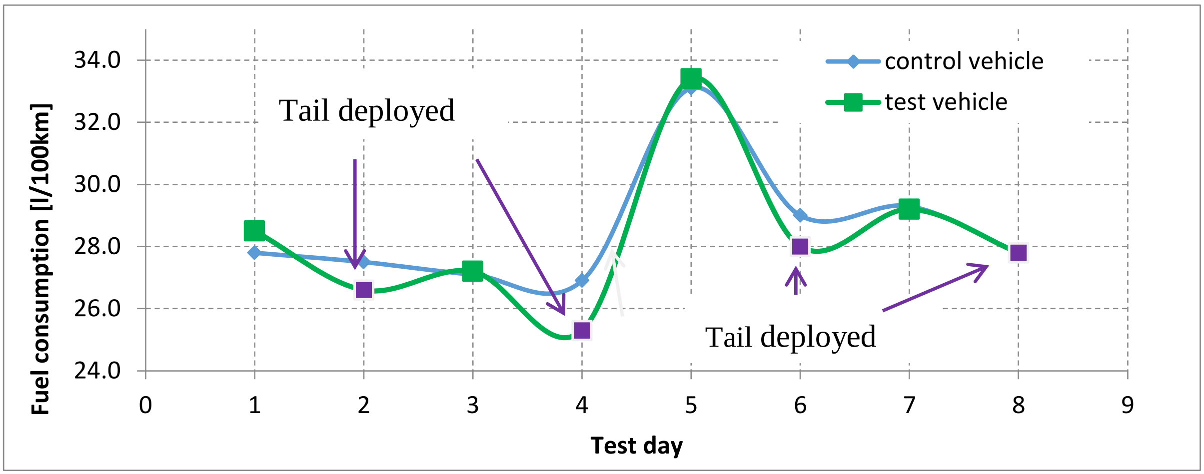

Figure 8 - Measured fuel consumption during Operational test 1

By applying equation (4), it is possible to determine the fuel savings. The fuel saving for this operational test has been determined to be 1.13 l/100 km. This fuel savings incorporates changing vehicle parameters like vehicle weight and speed, having a large influence on the actual fuel economy.

Operational Test 2

The second public road test was conducted with a Dutch fleet. For a duration of 35 weeks (from February to December) the fuel consumption was monitored. The testing period was divided in a test period and a baseline period. All speeds are considered, and because of the duration of the test, also seasonal changes are included in the test (see Figure 9). Because only a single vehicle was used, equation 4 cannot be applied directly, and a least squared fit of a quadratic formula was applied. The result can be seen below. The result of this analysis shows that an average saving of 0.98 l/100 km was achieved.

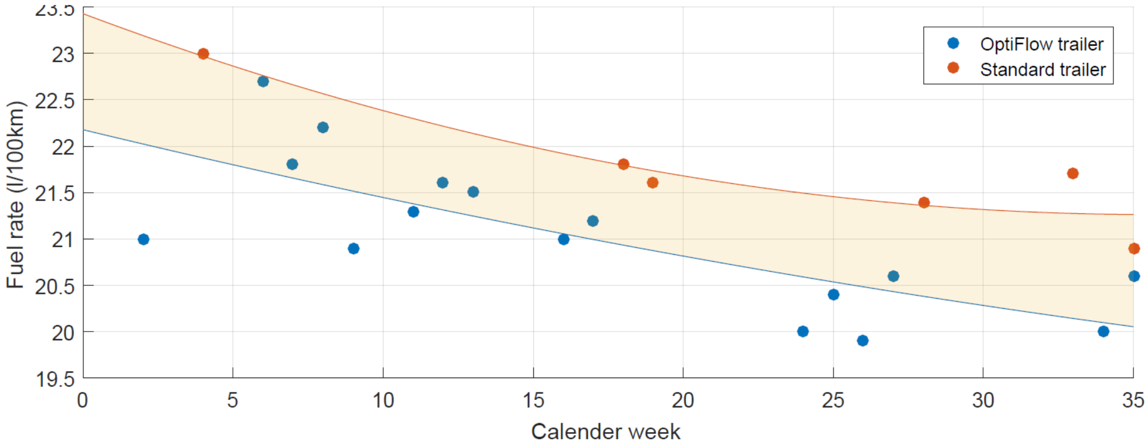

Figure 9 - Measured fuel consumption during Operational test 2

7. Comparison

With all the stages of testing completed, it is possible to make an overview of all the results. For the first two stages, the CFD and the wind tunnel test, the reduction is expressed in drag coefficient C_D, whereas the later steps all express the savings in l/100 km. To convert the computer simulation and wind tunnel results,the method of VECTO is used as it features the most advanced models for the engine, axles, wheels and aerodynamics.
The VECTO long haul trajectory (including road gradients) is simulated using the generic class 5 tractor of VECTO, featuring a 12.7l, 325 kW engine, with a reference load of 19.3 ton. The resulting overview is shown in Table 4.

Table 4 - Overview of all results

Method	ΔC_D	Fuel saving [L/100 km]	Additional realistic condition	Remarks
CFD	0.040	0.70†	-	Long haul trajectory, all speeds incorporated
Wind tunnel	0.046	0.80†	Yaw angle	
Track test	-	1.22	Weather, road, tires, engine, geometry	Constant vehicle speed of 85 km/h
One day test	-	1.50	Driver influence	Constant vehcle speed of 90 km/h
Operational test 1	-	1.13	Loading, Traffic, Low speeds	t: 8 days
Operational test 2	-	0.98	Seasonal influence	t: 35 weeks

†: Converted using VECTO

Normally, one would expect the savings to go down with added realism, as the realism induces chaotic uncontrolled flow behavior, which is generally not the design point. However, going from CFD to wind tunnel there is a significant increase in savings. This is partly because this is still early in the design phase. As such, every calculation and experiment is used to improve the design of the tail. Design improvements were added when going from the CFD to the wind tunnel, and going from the tunnel to the track test. Additionally, to calculate the fuel savings based on drag coefficient reduction results the simulation tool VECTO is used. This tool (correctly) assumes a certain long-haul trajectory that includes, amongst others, a velocity profile and road gradients, and assumes a cargo weight. All these parameters have an influence on the fuel consumption. Especially the speed profile defines largely the potential fuel saving of aerodynamic drag reduction devices.
Going to the track test (with constant highway vehicle speeds), the fuel savings increased again, this can be attributed to the stronger than usual wind during the conducted track tests. This increases the aerodynamic drag, and thus also the potential for aerodynamic drag reduction.
During the one day test, the aerodynamic savings were higher than during the track test. This can be attributed to the speed at which the vehicles were driving. The track test was conducted a speed of 85 km/h (the legal limit in the Netherlands), whereas the vehicles were driving 90 km/h during the one-day test. If one assumes that the drag is dependent on velocity squared, this results in a difference of 12%, partly explaining the difference. The difference in speeds is caused by commercial incentives. The customer that is the test-partner determines the testing speed during the one day test.
Going to the first operational test, the result decreased significantly, as it includes loading (weight) differences, and lower speed data.

This also holds for the longer operational test, where all speeds are considered. Added to this are seasonal influences, for example, heavy snow during the winter, which might cause more traffic jams, thereby lowering the average speed and the aerodynamic savings.
Finally, the effect of the driver behavior (the way the vehicle accelerates and decelerates) cannot be neglected. On a test track, the driver is cancelled out due to the constant speed throughout the test, while this is not the case when conducting operational tests on the public road.

8. Conclusion and Discussion

A complete set of aerodynamic design tools are used to develop successfully an aerodynamic drag reduction devices for semi-trailers. Numerical simulations indicated a first potential drag reduction of 40 drag counts. This was increased to 46 drag counts by implementing design changes while conducting scaled wind tunnel test incorporating yaw angle effects.
Next several full-scale fuel economy tests were performed with the tail, both a test track and public roads. The broad range of fuel saving results (1.0-1.5 l/100km) obtained with the same aerodynamic drag reduction device indicates that there are many vehicle and environmental parameters having an influence on the outcome. Additionally, it indicates that real fuel economy improvements tests on public roads are necessary to address the performance of aerodynamic drag reduction devices during realistic operational conditions. The results obtained from public road testing are in general lower compared to the track test savings due to mainly the effect of driver behavior, different vehicle speed profiles, road gradient in combination with vehicle weight.

Determining the performance of fuel saving technologies in a controlled environment, i.e. VECTO, numerical simulations, wind tunnel testing, enable the possibility to compare different solutions in a proper way. Nevertheless, determining its performance in its real environment, including changing weather conditions, is necessary to define its actual performance.

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