SAE TECHNICAL PAPER SERIES

2000-01-3056

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Reprinted From: Intelligent Vehicle Technology (SP-1558)

The Engineering Society For Advancing Mobility Land Sea Air and Space® INTERNATIONAL

2000 Future Transportation Technology Conference
Costa Mesa, California
August 21-23, 2000

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

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Fuel Consumption Reduction in a Platoon: Experimental Results with two Electronically Coupled Trucks at Close Spacing

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ABSTRACT

This paper presents the fuel consumption reduction experienced by two heavy-duty trucks driving at close spacing. The trucks were coupled without any mechanical contact using an “Electronic Tow Bar” developed within the European project PROMOTE-CHAUFFEUR at DaimlerChrysler. The experiments were carried out on a level test track with constant velocities and with spacing between 6 and 16 m. As expected from other studies, both trucks experienced a considerable fuel consumption reduction compared to drives in isolation. At a velocity of 80km/h and a spacing of 10 m the measured fuel consumption reduction was of about 21 percent for the trail truck which had a total weight of 28 t. An extrapolation of the results for other vehicle weights is also presented.

INTRODUCTION

The growth of the volume of goods transported by road in the European Union will result in dramatic increase of travelling time and of freight transport costs. In PROMOTE-CHAUFFEUR, a joint European project, unconventional solutions and innovative systems to improve the capacity utilisation of the existing road network were investigated. Within this project, a driver assistance system for automated vehicle following (Electronic Tow Bar) was developed at DaimlerChrysler for two heavy-duty semi-trailer Mercedes-Benz trucks of type ACTROS 1853 LS. While the lead truck is driven manually, the trail truck is completely operated by a vehicle controller and follows the lead truck automatically at a very short distance (6-16 m) in the velocity range from 0 up to maximum speed of 80 km/h.

As a result of the short following distance the road capacity can be increased. Furthermore the fuel consumption can be reduced because of the experienced drag reduction resulting from the slipstream effect. Some studies have already investigated this drag reduction in platoon such as [1], [2] or [3]. However these studies focus on drag reduction and not directly on fuel consumption reduction. For trucks fuel consumption was investigated at spacing larger than 20 m in [4]. Other studies focused on the influence of misalignments in the platoon on drag reduction such as [5] or [6]. To quantify the fuel savings especially for a two truck platoon at spacing shorter than one vehicle length, experimental measurements were done with the DaimlerChrysler CHAUFFEUR Electronic Tow Bar system.

OVERVIEW AND THEORETICAL ASPECTS

In the following section some theoretical simple models as well as related studies for fuel consumption and drag force reduction are presented.

INFLUENCE OF DRAG FORCE ON FUEL CONSUMPTION

The fuel consumption F of a vehicle can be calculated from the energy needed to overcome the driving resistances R.

With the assumption that the road is level and that the vehicle velocity is constant, the fuel consumption F can be considered, in a first approximation, as proportional to the drag force R_D and the rolling resistance R_R ([7]):

$$F \approx k\left(R_D + R_R\right) \tag{1}$$

where k is a proportionality factor which depends on e.g. engine properties, engine rotation speed and actual gear.

The drag force is expressed as

$$R_D = \frac{1}{2}\rho \cdot A \cdot C_D \cdot v^2, \tag{2}$$

where ρ is the air density, A the cross-sectional area of the vehicle, C_D the drag coefficient and v the driving speed (assuming no wind).

The rolling resistance R_R on a level road is given by

$$R_R = f_{roll} \cdot m \cdot g \tag{3}$$

where m is the vehicle mass, g the gravitational acceleration. In a first approximation the rolling coefficient f_{roll} can be considered as constant.

As a consequence, fuel consumption F from equation (1) can be expressed as

$$F \approx k \cdot \left(\frac{1}{2} \rho A C_D v^2 + f_{roll} mg \right). \tag{4}$$

DRAG RESISTANCE REDUCTION AND FUEL CONSUMPTION REDUCTION

The fuel consumption reduction ΔF compared to a reference state (denoted by the subscript $_0$) can be defined by:

$$\Delta F = \frac{(F_0 - F)}{F_0}, \tag{5}$$

where F_0 is the fuel consumption in the reference state.

The drag coefficient reduction ΔC_D can be defined by:

$$\Delta C_D = \frac{(C_{D0} - C_D)}{C_{D0}} = (1 - \frac{C_D}{C_{D0}}), \tag{6}$$

where C_{D0} denotes the drag coefficient in the reference state.

With these definitions, the fuel consumption reduction ΔF based on the simple model presented in equation (4) can be expressed as a function of the drag coefficient reduction ΔC_D. Under the assumption that the circumstances of the measurement of the reference fuel consumption F_0 are nearly the same as for the actual measurement F, the proportionality factor k in equation (4) and the vehicle velocity can be considered as constant. As a consequence the fuel consumption reduction can be determined by

$$\Delta F = \frac{\frac{1}{2} \rho A v^2 \cdot (C_{D0} - C_D)}{\left(\frac{1}{2} \rho A C_{D0} v^2 + f_{roll} mg \right)} \tag{7}$$

and further

$$\Delta F = \eta \cdot \Delta C_D \tag{8}$$

with

$$\eta = \eta_{cv} = \frac{1}{1 + f_{roll} \cdot \frac{g}{1/2 \cdot \rho} \cdot \frac{1}{v^2} \cdot \frac{m}{C_{D0} A}} \tag{9}$$

This influence coefficient η will be denoted by η_{cv} where the subscript $_{cv}$ indicates a constant velocity.

Note that this influence coefficient only depends on the rolling coefficient f_{roll}, the velocity v, the mass m, the reference drag coefficient C_{D0} and the cross-sectional area A. For simplification, the air density ρ and the acceleration due to the gravity g can be considered constant.

More detailed models can be found in [8] that take into account different scenarios (temporal variations of vehicle speed) in urban or highway environment. The influence factor η is somewhat different but still only depends on general vehicle and road parameters such as rolling coefficient f_{roll}, mass m, reference drag coefficient C_{D0} and cross-sectional area A. This influence coefficient calculated in [8] is given for an urban scenario as:

$$\eta = \eta_u = \frac{0.74}{1 + (0.0683 \cdot f_{roll} + 0.00134) \cdot \frac{m}{C_{D0} A}} \tag{10}$$

and for a highway environment as:

$$\eta = \eta_h = \frac{0.89}{1 + (0.0310 \cdot f_{roll} + 0.000126) \cdot \frac{m}{C_{D0} A}} \tag{11}$$

REDUCTION OF DRAG RESISTANCE IN A TWO-VEHICLE PLATOON

In the previous section theoretical relations between drag coefficient reduction and fuel consumption reduction were presented.

Due to the complexity of the aerodynamic problem, some theoretical models of the influence of spacing in a platoon on the drag coefficient reduction cannot yet be easily developed. Some theoretical aerodynamic studies focusing on simple geometrical shapes can be found in [9]. However results for road vehicles can only be obtained with vehicle models in wind tunnels or full-scale vehicles.

At the University of South California, this effect was first investigated on platoons consisting of two or three or four 1/8 scale model minivans in a wind tunnel ([1] or [10]). In a second step, measurements were performed with two experimental mechanically coupled full-scale minivans ([2]). The experimental runs were made on a dry lakebed near Victorville, California. The drag coefficients were determined for spacing shorter than one vehicle length. The results are shown in figure 1, where $C_D = C_d$ is the drag coefficient and $C_{D0} = C_{dref}$ is the reference drag of an experimental full scale minivan in isolation. The drag coefficient reduction is given in function of the spacing in vehicle lengths.

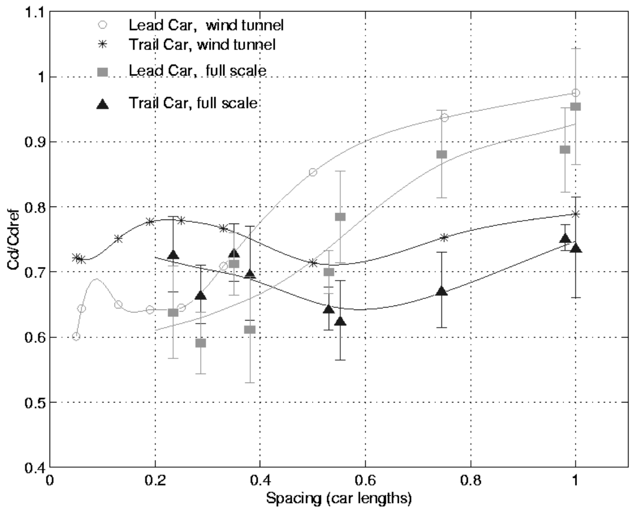

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Figure 1: Drag coefficient in a platoon of two full scale minivans (source [2])

Figure 1 shows that the trail minivan has a drag coefficient reduction between 25 and 35 percent depending on the spacing. The maximum drag coefficient reduction is reached at about 0.5 vehicle length. The lead minivan experienced some drag coefficient reduction too. It starts at a spacing of about 1 vehicle length and has a maximum of 40 percent at very close spacing.

Concerning heavy vehicles, drag coefficient reduction for commercial vehicles is considered in [3]. The results show a significant drag coefficient reduction in a platoon of two or three vehicles. The shape of the curves is somewhat different than for minivans: the curves do not cross and do not have any local maxima or minima. It may be supposed that the shape of the vehicle has a big influence on the drag reduction.

SYSTEM DESCRIPTION

The experiments were done with the DaimlerChrysler Electronic Tow Bar developed within the European Research project PROMOTE-CHAUFFEUR. With this special equipment the trucks could be operated at close and constant following distance without mechanical tow bar and with a constant velocity. So the influence of drag reduction on fuel consumption could be directly investigated.

THE ELECTRONIC TOW BAR

Figure 2 shows the semi-trailer trucks in Electronic Tow Bar operation. While the lead truck is driven manually, the trail truck is completely operated by a vehicle controller and follows the lead truck automatically.

Figure 2: The two DaimlerChrysler CHAUFFEUR trucks

The trucks are equipped with a diesel engine of type OM502 LA (with 530 hp) with exhaust turbocharger and charge-air intercooling. The mechanical transmission has 16 gears. The braking system is composed of friction brakes, an engine brake and a Retarder (RET). The standard Mercedez-Benz heavy-duty trucks of type ACTROS are equipped with an electronic drivetrain management (EAS). The EAS includes electronic control units for engine (FMR), for clutch (MKR), for gearbox (EPS) and for automated gear determination (AGE). In Figure 3 the essential components of the Electronic Tow Bar system are shown. All control units communicate via a Controller Area Network (CAN). In the CHAUFFEUR trucks the standard electropneumatic brake (EPB) has been modified. This modification includes a brake management to activate the engine brake and the Retarder as well as a supervision of the CAN communication. For the longitudinal and lateral vehicle guidance the Tow Bar-Vehicle-Controller (TVC) gives control signals to the engine, the brakes and the steering system. The TVC receives information from the lead vehicle by a Vehicle to Vehicle Communication (VVC). VVC is absolutely necessary for safety reasons (e.g. when the lead truck brakes suddenly) because the rear truck follows the lead truck at a very small distance. Additionally, the TVC gets information about the relative positions of the lead and the trail trucks from the DaimlerChrysler Image Processing system (IP). For this, at the back of the trailer of the lead truck, several infrared lights are fixed forming a special pattern.

For automated lateral guidance an electronic Steering Control System (SCS) was developed by one of the project partners within the CHAUFFEUR project. The SCS is structured as a redundant system. A main feature within the system approach is that, in any case, the driver has the possibility to override the SCS by using the steering wheel to steer manually. More information about the electronic tow bar system can be found in [11].

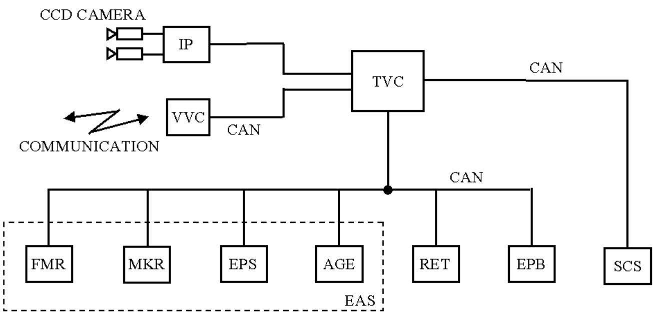

Figure 3: System components of the Electronic Tow Bar

DATA ACQUISITION

The fuel consumption was measured in both trucks by the system *EDM1404* of the company *automotive Mannesmann VDO Kienzle*: from information of a flowmeter and the actual velocity, it calculates the current fuel consumption in L/100km, the average fuel consumption in L/100km, the volume of consumed fuel in L and the driven distance in m with a cycle time of 10 s.

Additional vehicle state information (such as engine status, spacing between vehicle, actual gear) can be acquired from the TVC using the data visualisation software *RPOS* developed by the company *Vector-Informatik* via TCP/IP connection with a cycle time of 1 s.

CALCULATION OF THE AVERAGE FUEL CONSUMPTION

For each experiment the average fuel consumption was calculated over the driven distance using two different methods.

In the first method the average fuel consumption F_1 is defined as the average of the actual fuel consumption F_{ac} for the driven course d:

$$F_1 = \frac{1}{d}\int_{s=0}^{s=d} F_{ac} \cdot ds$$

where F_1 is given in L/100km, F_{ac} in L/100km and d in km respectively.

The second method calculates the average fuel consumption F_2 as the ratio of the volume of consumed fuel V_{total} and the driven course d:

$$F_2 = \frac{V_{total}}{d/100}$$

where F_2 is in L/100km, V_{total} in L and d in km.

To correct the small differences between F_1 and F_2 and thus obtain more reliability, the average fuel consumption F was calculated as the mean value of F_1 and F_2.

EXPERIMENTAL RESULTS

The experiments were carried out on the new DaimlerChrysler test track at Papenburg, Northern Germany in two test rows with constant velocity (80 km/h and 60 km/h). Each series consisted of measurements of the reference consumption with each truck alone and rides with both trucks in platoon at a spacing from 5 up to 16 m. In order to have the same experimental conditions for all measurements, each ride was carried out on the entire 12 km long oval level track. Furthermore the tests in each series were done successively (wind considered as constant) as far as it was possible and with the same gear. So the assumption that the proportionality factor k (equation (1)) remains constant could be fulfilled. The lead truck with an empty trailer had a total weight of about 14.5 tons. The trail vehicle was loaded and had a total weight of 28 tons.

In the first series of experiments the trucks had a constant velocity of 80 km/h and the spacing was either 6.7, 7, 8, 10, 12, 14 and 16 meters. In the second series the velocity was 60 km/h and the spacing was either 5, 6, 8, 10, 12, 14 or 16 meters. These separating distances stay in the range of one vehicle length which is of 16.5 m. In Figure 4 shows the results for the trail truck (28 t) and figure 5 for the lead truck (14.5 t) respectively. The reference fuel consumption F_0 of the lead truck was of about 24.5 L/100km at 80 km/h and about 20 L/100km at 60 km/h. For the trail truck it was of about 28 L/100km at 80 km/h and of about 22 L/100km at 60 km/h.

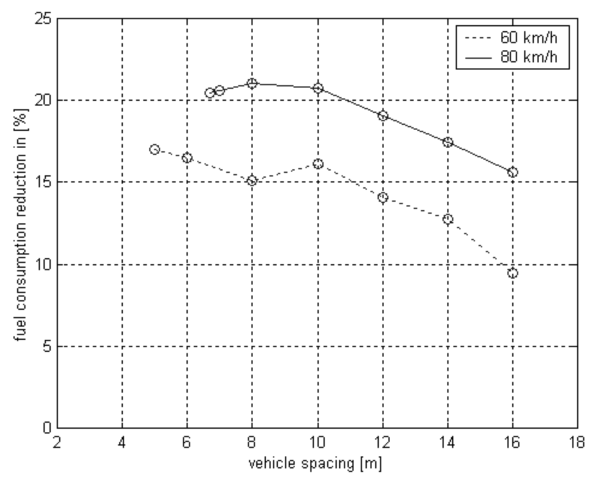

Figure 4: Fuel consumption reduction for the trail truck (28t)

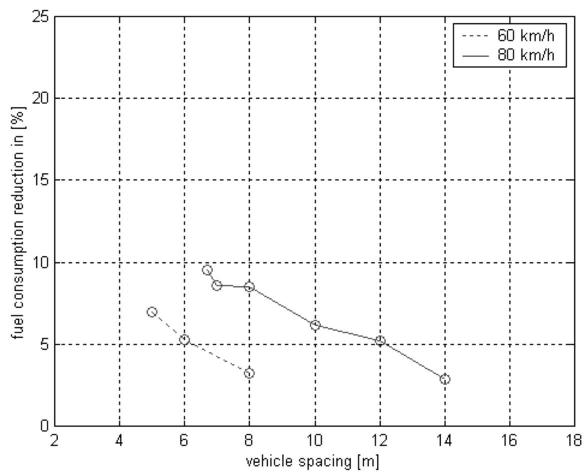

Figure 5: Fuel consumption reduction for the lead truck (14.5t)

In figure 4 one can see that the trail truck experienced a considerable fuel consumption reduction in the whole range of spacing for both velocities. When the spacing gets closer, the reduction increases and reaches a nearly constant value for spacing closer than 10 m. The resistance of the wind is proportional to the square of velocity (see equation (2)), therefore the fuel consumption reduction is smaller for 60 km/h than for 80 km/h. The fuel consumption reduction ranges from 15 to 21 percent at 80 km/h and from 10 to 17 percent at 60 km/h. At a velocity of 80 km/h and a spacing of 10 m, the measured fuel consumption reduction was about 5.9 L/100km, i.e. 21 percent of the fuel consumption of the trail truck in isolation. At a spacing of 10 m spacing and at a velocity of 60 km/h, it was about 3.5 L/100km i.e. 16 percent.

The error of the fuel consumption reduction is of about 3 percent at 80 km/h. This is due to the average accuracy of the measurement system which is about 0.4 L/100km. With decreasing velocity the fuel consumption decreases too. Therefore the accuracy of the fuel consumption reduction at 60 km/h increases to about 4.5 percent.

Figure 5 shows the fuel consumption reduction for the lead truck. Since this truck was not loaded, its fuel consumption reduction is low. Therefore measurements at spacing larger than 8 m at 60 km/h and 14 m at 80 km/h are not accurate enough (fuel consumption reduction of less than 3 percent) and are not presented. Nevertheless a fuel consumption reduction between 5 and 10 percent at 80 km/h and between 3 and 7 percent at 60 km/h can be observed. For the lead truck the fuel consumption reduction always increases with decreasing spacing.

From the fuel saving point of view, a spacing of 10 m between the trucks seems to be a good one. The fuel consumption reduction for the trail truck seems to stay constant or does only increase slowly when the spacing gets closer. Furthermore, the lead truck also experiences a fuel consumption reduction at this spacing.

EXTRAPOLATION WITH SIMULATION

The Electronic Tow Bar trucks had a total weight of 14.5 and 28 tons. However trucks can have a total weight of 40 tons in Europe. From the theory the influence of the drag reduction on fuel consumption reduction decreases when the mass increases. To extrapolate the measurements to other masses and velocities, a simple simulation can be used.

Based on the model presented in equation (8), the fuel consumption reduction can be calculated from drag coefficient reduction ΔC_D of the trucks and the influence coefficient η can be calculated for different masses.

The drag coefficient reduction ΔC_D for both lead and trail truck can be obtained from the measured fuel consumption reductions using equation (8). Since the trucks had a constant velocity v, the influence factor η can be calculated as η_{cv} from equation (9). Table 1 shows the value of the influence factor η for each truck at velocities of 60 and 80 km/h calculated with following values: f_{roll}=0.006, C_{D0}=0.53, A=9m^2, which were valid during the experiments.

	60 km/h	80 km/h
lead truck (14.5 t)	0.5009	0.6408
trail truck (28 t)	0.3420	0.4803

Table 1: Values of the influence factor η

The calculated drag reduction for both experimental trucks are shown in figure 6.

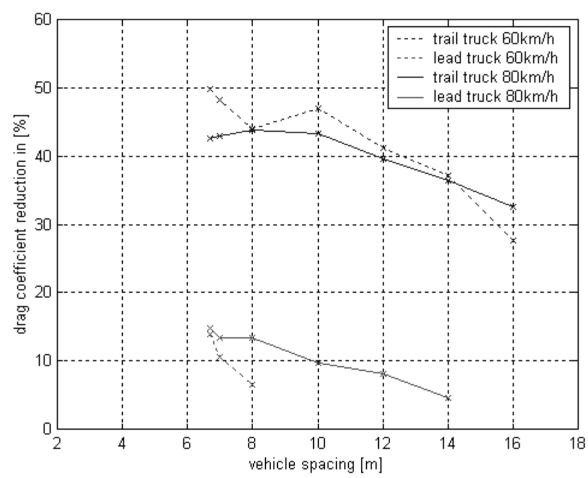

Figure 6: Drag coefficient reduction for experimental trucks

The two curves for the trail truck show a good agreement. This shows that the simple fuel consumption model can be applied to extrapolate to other velocities and other masses. The bad accuracy of the measurements for the lead truck could be the reason for the disagreement of the curves representing the drag coefficient reduction for this vehicle.

However the drag coefficient (C_D) reduction for both trucks are comparable to the reduction obtained in earlier studies with minivans and commercial vehicles ([2], [3]). The curves obtained for trucks show more similarities to those for commercial vehicles what seems to confirm that the vehicle geometry has a big influence for C_D reduction.

In order to have a better accuracy for the extrapolation, the drag coefficient reductions experienced by both trucks at 80 km/h (which have the best accuracy) were implemented in the simulation. Figure 7 shows the extrapolated fuel consumption reduction for the trail truck for masses of 14.5, 28 and 40 tons at a velocity of 80 km/h.

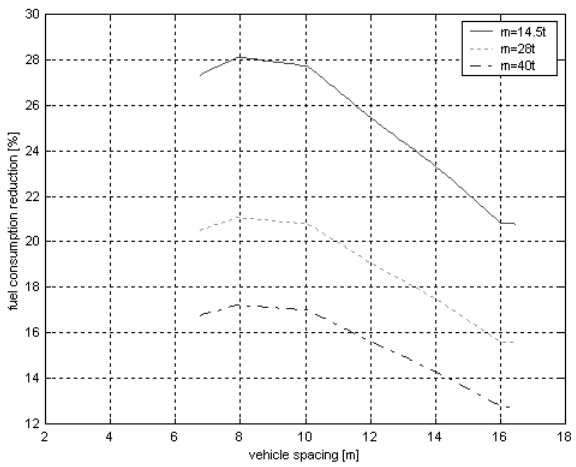

Figure 7: Measured and extrapolated fuel consumption reduction for the trail ACTROS truck (v=80km/h) for different masses

Since the rolling resistance is proportional to the mass, the influence of the air resistance increases when the mass decreases and vice versa. As a consequence, the fuel consumption reduction which a fully loaded trailer truck would experience is smaller than the measured one for 28 t as can be seen in figure 7. With a total weight of 40 t a Actros truck driving at 80 km/h should save approximately 17 percent of fuel when following another Actros truck at 10 m spacing.

As a consequence of the influence of the mass, the lead truck should experience a lower fuel consumption reduction with a total weight of 28 or 40 tons than the one measured in the experimental runs as can be seen in figure 8.

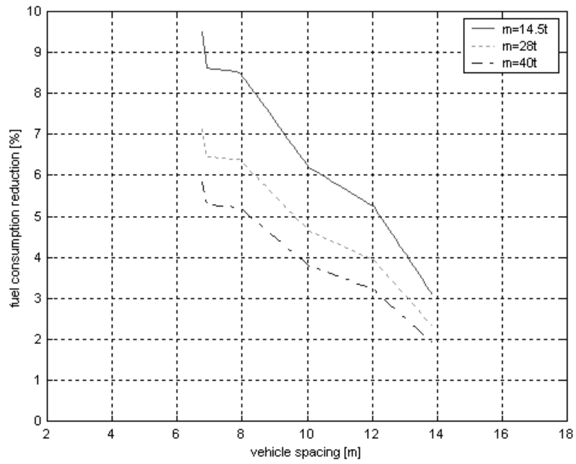

Figure 8: Measured and extrapolated fuel consumption reduction for the lead ACTROS truck (v=80km/h) for different masses

CONCLUSION

Experimental runs were carried out on the new DaimlerChrysler test track in Papenburg to quantify fuel savings for an Electronic Tow Bar system with 2 heavy-duty ACTROS semi-trailer trucks at close spacing. The main result of these measurements is that both trucks experienced a considerable fuel consumption reduction compared to runs in isolation.

The fuel consumption reduction for both trucks increases when spacing decreases. For the trail truck which had a total weight of 28 tons it was of about 21 percent at 10 m spacing (which is about the half of a truck length) and at a velocity of 80 km/h. The lead truck (14.5 tons) also experienced a fuel consumption reduction of about 7 percent at this spacing and at this velocity. At spacing closer than 10 m no substantial reduction of the fuel consumption was observed for the trail truck.

To extrapolate the measured reduction to other masses and velocities, a simple model was used. This model takes into account that when the velocity decreases or when the mass increases, the proportion of drag resistance compared to the rolling resistance decreases, therefore the fuel consumption reduction decreases as well. With this simulation a fuel consumption reduction of 17 percent for the trail truck with a mass of 40 tons at 10 m spacing and at a velocity of 80 km/h can be predicted.

The experimental results presented in this paper are restricted to two electronically coupled ACTROS semi-trailer trucks and have been measured under nearly ideal conditions on a level test track. Further experiments on public highways and with different loads should be done to verify and extend these results for real traffic conditions.

ACKNOWLEDGEMENTS

This work was done as a preparation for the PROMOTE-CHAUFFEUR follow-on project CHAUFFEUR II. The authors would like to thank the European Commission for sponsoring the PROMOTE-CHAUFFEUR project and the Electronic Department, “Direction de la Recherche” of Renault for their support in this pre-investigation.

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