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TNO report

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Real-world impacts of truck driving with Adaptive Cruise Control on fuel consumption

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1 Background of this report

This concise report consists of an analysis that is conducted in relation to the Ursa Major Neo Integrator Connected Truck Trials project (060.36265). This project aimed to assess the real-world impacts of trucks driving with Adaptive Cruise Control (ACC) on fuel consumption, driver behaviour and logistics. During 15 weeks experimental tests in various driving campaigns by a naturalistic driving study were conducted with a total of 25 weeks of data logging.

The fuel consumption analysis is co-funded by the CATALYST Living Lab. For the purposes of reporting the project results to NWO, this report only presents the results of the CATALYST-funded part of the research. The full report (including more detailed information on the methods applied) and the Dutch summary can be found below.

- Van Kempen, E.A.. De Ruiter, J.M., Souman, J.J., Van Ark, E.J., Deschle, N., Oudenes, L., Van Horst, A.R.A., Janssen, R. (2021). Real-world impacts of truck driving with Adaptive Cruise Control on fuel consumption, driver behaviour and logistics – results from a hybrid field operational test and naturalistic driving study in the Netherlands. The Hague: TNO. TNO 2021 R10516.
- Van Kempen, E.A. (2021). Real-world impact van het rijden met Adaptive Cruise Control op het brandstofverbruik, de chauffeur en de logistiek. Den Haag: TNO. TNO 2021 R10709.

2 Fuel consumption and emissions[1]

2.1 Introduction

We examine the impact of current ACC systems on fuel consumption and CO_2 emissions. Many claims have been made about the possible reduction in fuel consumption and CO_2 emissions when driving in truck platoon formation at short gap distances between the vehicles. With regard to following distances of less than 10 meters, a fuel consumption reduction of up to 16% has been reported (Van Ark et al., 2017),[2] however current generation ACC systems only allow for a minimum following interval of 1.4 seconds, which corresponds to 31 m at 80 km/h. We are, therefore, interested in usage of ACC and the impact it has on fuel consumption and CO_2 emissions. Specifically, we aim to investigate what the effects are of using various ACC modes/settings, and whether the truck drives in convoy formation. These research questions are addressed monitoring multiple trucks during real-world driving.

This results in the following sub questions:

- RQ 1.1 What is the impact of using ACC (or not) on fuel consumption?
- RQ 1.2 What is the impact of using different ACC modes (and settings) on fuel consumption?
- RQ 1.3 What is the impact of trucks driving in convoys on fuel consumption?

2.2 Literature

In this section we provide an overview of the developments with respect to fuel consumption and truck platooning. We do this by highlighting the most important studies and presenting the latest developments in the European ENSEMBLE project.

From an early stage in the development of truck platooning, one of the expected benefits of the technology is reduced fuel consumption. As trucks are driving at a closer gap distance, the aerodynamic drag coefficient of each vehicle decreases depending on its position in the platoon (Tsugawa, 2016). Also, automatic speed control and cooperative vehicle following control can smooth speed variations in traffic, which can save energy and as such reduce fuel consumption and related CO_2 emissions.

Van Ark et al. (2017) summarised the results of various studies on truck platooning and the effect on fuel consumption (PROMOTE, Auburn-Peleton, Japan – Energy ITS, PATH, SARTRE). They report team savings – the average savings of all vehicles in a platoon – up to 16%. These numbers are mainly based on experimental test-track studies such as SARTRE. Van Ark et al. (2017) estimated team fuel savings for several platooning capabilities with varying gap distances (at a speed of 80 km/h): 6% at 1.0 s. or 22m., 8% at 0.6 s. or 13 m. and 10% at 0.3 s. or 6.7 m.

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[1] The analysis reported in this chapter is co-funded by the CATALYST Living Lab

[2] For an extensive discussion of available fuel savings figures at the start of 2019 see also Veldhuizen et al, 2019.

Since the Van Ark et al. (2017) literature summary however, newer insights have been emerging. For example fuel consumption effects of truck platooning at larger gap distances (20-70 m.) were researched (Veldhuizen et al., 2019). Figure 1 summarizes the fuel consumption results of the leading and the following vehicle in a 2-truck platoon in the study of Veldhuizen et al. (2019) relative to earlier studies. For the following vehicle, at the largest distance of 50 m savings of 9.0 ± 2.8% were achieved. Decreasing the distance to 40, 30 and 20 m did not yield any significant savings over a following distance of 50 m. The authors conclude that for the following vehicle at European legal distances (50 m) the savings of platooning are significant, and that the potential for increasing the savings by reducing the separation distance is rather limited.

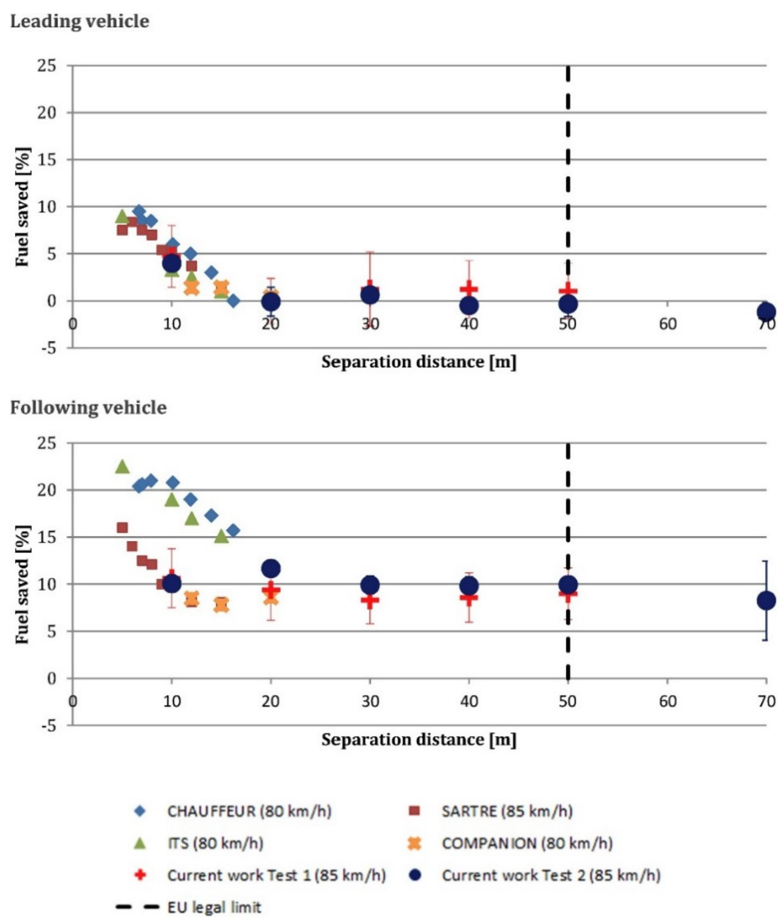

Figure 1 – Fuel economy platooning results Veldhuizen et al. (2019) compared to earlier studies (Adapted from: Veldhuizen et al.,2019)

It should be remarked that comparing these studies is challenging, since testing conditions (test track versus real-world), weather conditions, testing protocols (no clear protocol versus SAE J1321 Type II fuel economy protocol) and truck vehicle profiles (EU cab-over versus USA torpedo model) vary across studies (see Table 1). Also, information on conditions such as weight and load of the vehicles were not equally available. Lastly, most studies researched short gap distances, below 20 meters (less than 1.0 second at a speed of 80 km/h).

Table 1 – Positioning of this research with respect to previous studies and study conditions

Project/ Research	Test protocol	Speed (km/h)	Gap distance (m).	Truck platoon	Truck profile	Load	Weather
Auburn – Peleton (2017)	SAE J1321 Type II fuel economy protocol	105	9,12,15, 23,45.	2 truck platoon	Articulat-ed tractor-trailer	30t. / truck-trailer	
CHAUFFEUR/ PROMOTE (2000-2003)	By flow measureme nt (3% reliability)	80	8,10,12,1 4	2 truck platoon	No wind deflector s on tractors	Lead truck 14.5t.; following truck 28t.	
EDDI (2019)	Real-world	80	15	2 truck platoon		Dummy and actual goods (from sept.)	Varying summer, autumn, winter: Aug-Dec.
ITS (2013)	No clear protocol	80	5,10,15,2 0	3 truck platoon	Rigid body	Empty-loaded	
PATH (2004)	No clear SAE protocol mentioned	80, 89	3,4,6, 8,10.	2 truck platoon	Articulat-ed tractor-trailer	Empty-loaded. 14-28 t. / truck-trailer	
SARTRE (2013)	Extensive description (not SAE)	85	5, 12, 20, 25.	2 truck platoon	Rigid body	Unknown	Described
Veldhuizen et al. (2019)	SAE J1321 Type II fuel economy protocol	85	10,20,30, 40,50,70.	2 trucks, ACC	EU truck over cab	Unknown	January (1-4°C); August (12-24°C).
This research: Integrator Connected Truck Trials, ACC	Real-world (naturalistic driving, field operational test)	80	33, 50.	2 truck ACC convoy	EU truck over cab	Loaded, mean weight 38t	Varying autumn, winter: Sept-Feb

Next to the test track results of Veldhuizen et al. (2019), real-world platooning tests have been conducted. The EDDI project (MAN, DB Schenker) shows the results of real-world platooning at a gap distance of 0.7s. or 15m. (at a speed of 80 km/h). The fuel savings are 1.3% for the leading truck and 3-4% for the following truck. These are considerably lower than the expected fuel savings reported in earlier studies and can be explained by the fact that real-world conditions are more diverse than tests on a test track. Also, trucks on the road often undershoot the safe driving distance and as a result the net fuel savings effects of platooning in real traffic are lower (Brandt, 2019).

Lastly, the European Horizon 2020 project ENSEMBLE, where the six large OEMs collaboratively work on multi-brand platooning, closely follows the developments with respect to expected fuel savings as a result from platooning. ENSEMBLE recognises the potential fuel savings of 4-10% for the following vehicle at a following distance of 1.5 s. or 33 m. at a speed of 80km/h. ENSEMBLE expects the same savings when following the SAE testing protocol on a test track. However, when implemented in real-world driving a negligible effect is expected due to the distances already driven (including risky tailgating). The ENSEMBLE consortium now focuses on a platooning technology that adopts a gap distance of 1.4-1.6 s. or 33 meter, comparable to the current DAF ACC mode 1 settings. This implies that expected savings at following distances shorter than 30 m. as reported by Van Ark et al. (2017) and displayed in Figure 1 will not be of relevance in the implementation as foreseen by ENSEMBLE.

2.3 Methodology specifically for fuel consumption and emission analysis

In order to determine which sensors to use for data collection, we first determine the data needs for answering our research questions related to fuel consumption and CO_2 emissions. Table 2 shows what data needs to be logged, by which data type this is gathered, and which sensor is used for this purpose.

Table 2 - Fuel consumption: Research aims, the related data type and sensors, and the research questions which use the resulting conclusions.

Aim	Data type	Sensor	Question
Determine whether ADAS systems such as the ACC are enabled/engaged and at what speed	Information on ACC mode and vehicle speed	CAN bus	RQ 1.1 – 3
Determine real-world emissions of trucks	Vehicle emissions in the exhaust	Exhaust sensors	RQ 1.1 – 3
Determine distance and time headway to preceding vehicle	Radar distance information from the on-board radar sensor	CAN bus	RQ 1.2 – 3
Determine when convoy formation took place.	Calculation of inter-vehicle distances	CAN bus	RQ 1.3
	Relative truck GPS locations	CAN bus	
	Information on realised convoys	Information supplied by drivers/planners	
Determine the road type on which a vehicle is located	Location data: GPS longitude and latitude	GPS and map-matching using OpenStreetMap	*See Section 2.4*
Determine whether driving in convoy formation affects the aerodynamic resistance of the vehicle	Air pressure measurement in front of and under the vehicle	Pressure sensors	*See also Appendix A – 8.1.3* in Van Kempen et al. (2021)

For collecting the data as specified in Table 2, the Smart Emissions Measurement System (SEMS) is used (see Figure 2) which logs data at 1 Hz resolution. This system is developed by TNO for the purpose of logging real-world emissions, that is vehicles in natural driving conditions (as opposed to a controlled, laboratory environment) (Vermeulen, Spreen, & Vonk, 2014; Spreen, et al., 2016).

Figure 2: Smart Emissions Measurement System (SEMS), with sensors in the exhaust

Fuel consumption data was only used when the engine was at regular (hot) operating temperature, that is, when the engine coolant temperature was above 70 °C. The average fuel consumption was determined by dividing the total fuel used per subset of data, then dividing by total distance driven. This distance is calculated by integrating the speed of the vehicle over time. Fuel consumption can be determined either via the CAN bus (via the fuel rate signal), or via a sensor mounted in the exhaust. This sensor measures the mass flow in the exhaust, which can then be used to determine the CO_2 mass flow. For the five vehicles examined there is a deviation of around 1% between the total fuel calculated via the CAN bus signal, and the sensor (see Table 22 in Appendix A in Van Kempen et al., 2021). The median and interquartile range of fuel consumption is determined from the 1 Hz fuel consumption, which is subject to more fluctuation. The 1 Hz fuel consumption is determined per second, using the CO_2 mass flow (or fuel rate signal) and vehicle velocity.

2.4 Results

The measurement period ran over a period of six months, from 10/09/2019 to 29/02/2020. Routes were driven as usual, which included trips throughout the Netherlands, but also across Europe (Figure 3). During this time, the 9 vehicles (Trucks 1a, 1b, 2a, 2b, 3a, 4a, 4b, 5a, 5b) drove more than 325 000 kilometres and used around 100 000 L of fuel (Table 3). We note that Truck 2a has logged significantly less kilometres, in retrospect likely due to faulty hardware.
Most of the time is spent either idling at low speeds, or at speeds above 75 km/h (Figure 4). Map matching was used to categorise the road types on which the trucks drove on during this time period. 1% of the distance was driven on urban roads, 3% on rural roads, 40% on motorways, and 56% on roads that could not be categorised (for more information see Table 23 in Appendix A in van Kempen et al., 2021).

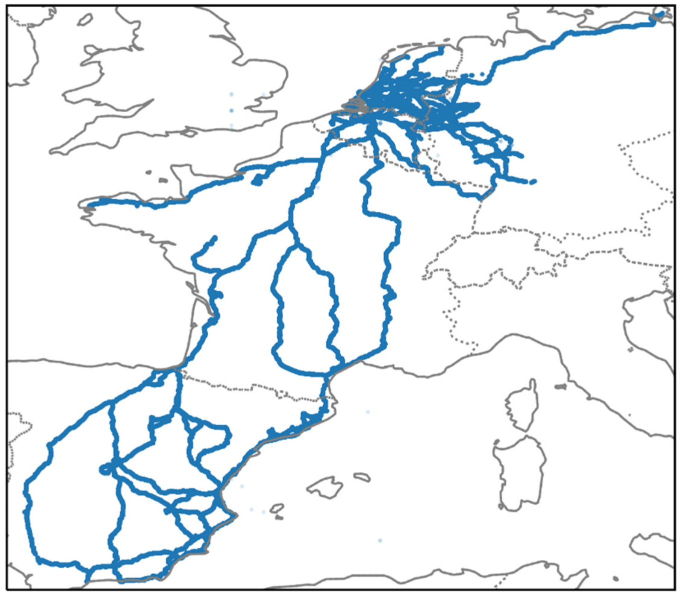

Figure 3 - Routes driven over the measurement period

Table 3 - Different statistics determined for the measurement period 10/09/2019 – 29/02/2020. Note that Truck 4a – 5b were not fitted with sensors; the fuel use is determined using OBD signals.

Name	Distance [km]	Time [h]	Average Speed [km/h]	Total Fuel [L]	Average Fuel [L/100km]
Truck 1a	30 930	700	44	9 152	29.6
Truck 1b	51 848	913	57	14 895	28.7
Truck 2a	13 368	276	48	5 076	38.0
Truck 2b	56 559	1 180	48	20 026	35.4
Truck 3a	39 378	549	72	10 930	27.8
Truck 4a	46 294	958	48	11 165	24.1
Truck 4b	36 312	728	50	9 247	25.5
Truck 5a	31 375	677	46	7 973	25.4
Truck 5b	46 704	900	52	11 156	23.9
Total	**352 767**	**6 880**	**51**	**99 621**	**28.2**

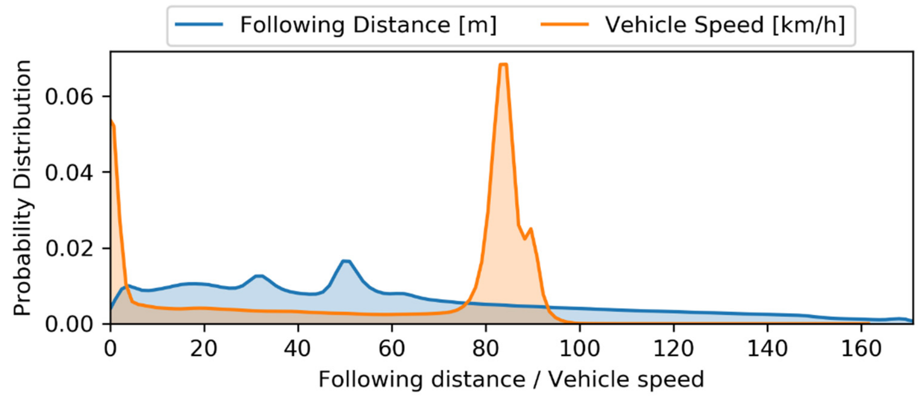

Figure 4 - Distribution of the following distance (or distance to the vehicle in front, blue) and vehicle speed (orange), for all driving during the campaigns

In the examination of the effects of ACC on real-word fuel consumption, we would primarily want to consider the effects based on the situations where this is most used: during long distance driving on the motorway. However, as more than half the kilometres driven were on roads that could not be classified, it is decided to used speed as a cut-off point: we will primarily consider driving at speeds higher than 75 km/h (referred to from here on out as high speed). We note here, that the mean fuel consumption for all vehicles (at all speeds) during this study is calculated as 28.2 L/100 km, which is slightly lower than the 29 L/100km previously published by TNO in 2016. (Ligterink, Zyl, & Heijne, 2016), perhaps due to loading conditions. On motorways the average fuel consumption is 27.5 L/100km, while at high speeds, the average fuel consumption is 27.0 L/100km.

2.4.1 *Implications of real-world driving*

During real-world driving, vehicles are subject to large variations in driving conditions. The vehicles drive on various routes, with differing traffic, weather, and road conditions. Furthermore, the payload also varies per trip. Especially driving dynamics (speed and acceleration during driving) and payload have a significant impact on fuel consumption. An initial examination of the correlation between fuel consumption and ACC modes and convoying was performed (as documented in Appendix A – 8.1.2 in Van Kempen et al., 2021). However, without accounting for the payload and driving dynamics, the observed effects can be biased by operating conditions with a heavy payload, or conditions on specific routes with specific payloads.

The influence on fuel consumption by the factors payload and driving dynamics are considered and accounted for in the following analysis. The payload, or the total vehicle weight, is estimated from the data itself. Payload can be considered the largest fuel consumption influencing factor. To estimate the vehicle weight, one can consider the high power consumption at hard acceleration. Furthermore, the power consumption at constant speed provides an estimate of the driving resistance, which also depends on vehicle weight. Using the calculated total mass, and the velocity and acceleration at each second of each trip, the expected CO_2 emission can be estimated. Investigating the difference between the actual fuel consumption and that expected based on the physical factors mentioned above, highlights fuel consumption dependencies besides these factors.

2.4.2 *Percentages reduction in fuel consumption for different ACC settings*

The fuel consumption dependency of ACC modes is investigated by examining the dependence on the headway (or following) distance, i.e. the distance between the truck in question and the vehicle in front of it. The residuals showing the effect of distance, and the typical distances of the ACC modes, can be combined with the average emissions to show the influence of these settings.

As shown in Figure 5 (top panel) there are significant decreases in fuel consumption at following distances corresponding to the ACC modes 1, 3, and 4: 33, 50, and 62 m.[3] Furthermore, Figure 6 shows differences in how ACC is employed by the different drivers. Truck 1b shows clear decreases in fuel consumption at 33 and 50 m, while Truck 2a only shows a decrease at 62 m.

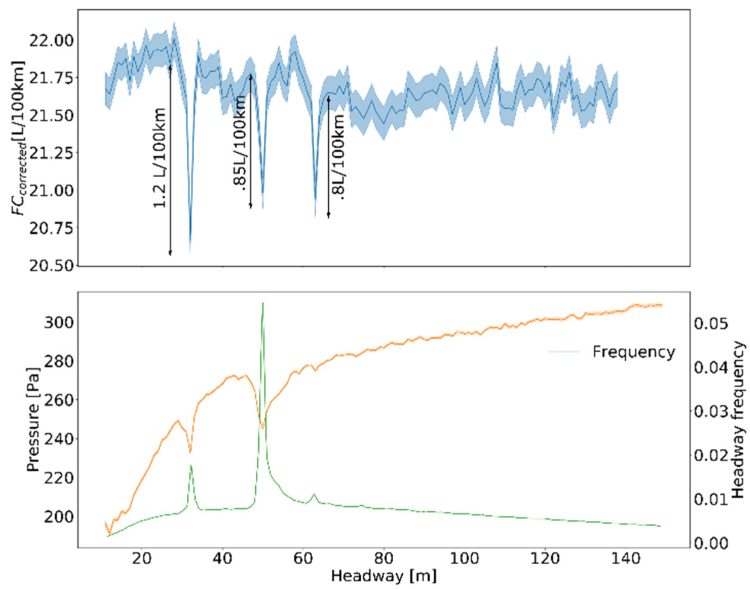

Figure 5 – Aggregated results for the fuel consumption and front pressure for the four vehicles equipped with pressure sensors. On the top panel the fuel consumption (blue) and the headway frequency (green) as a function of the distance headway are shown. The shaded blue region denotes the standard error of the fuel consumption. On the bottom panel the pressure as a dependence on the headway is depicted. The relative extrema correspond to headway distances around 33, 50 and 62 m (associated with ACC mode 1, 3 and 4).

To further examine these decreases, the pressure differences on the front of the vehicle is investigated, as shown in the lower panels of Figure 5 and Figure 6. The general trend shows a decrease in the pressure with respect to decreased following distance (as one might expect), with sharp decreases at the distances corresponding to the ACC modes.

[3] Note that ACC 4 was not part of the driving campaigns but is included here for completeness.

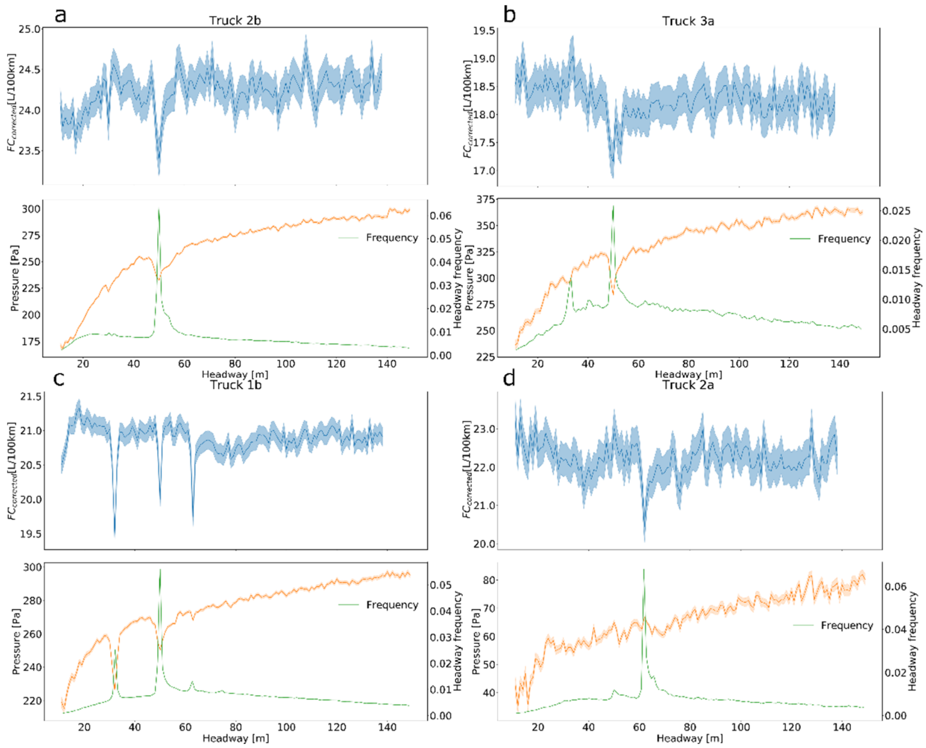

Figure 6 – Fuel consumption, front pressure and headway distribution for the four trucks equipped with sensor pressure separately. In each subfigure a) to d) the top panel shows the fuel consumption in blue. The thick line stands for the mean value whereas the shaded area indicates the standard error. The bottom panel shows the pressure measured at the front of the vehicle (orange) and headway frequency distribution (green). A reduction in fuel consumption and pressure is observed for the most frequent headway distances, which correspond to the headway distances associated with various ACC modes.

The reduction of fuel consumption is best expressed in terms of absolute numbers, as it is related to the change in air drag, and only partly to the change in dynamics. The reduction varies from 0.8 to 1.2 L/100 km, from the largest (62 m) to the smallest (33 m) headway. Given a typical fuel consumption of 22 L/100km for constant velocity on the motorway, the fuel consumption reduction is 4.3 to 5.6% from 50 metres to 33 metres headway respectively. Among the trucks there is about 30% variations in the reduction percentages and about 20% variations in the absolute reductions in litres per 100 km for the cases were the ACC mode was applied amply. Some ACC modes were applied less in certain trucks and no significant conclusions can be drawn for these cases. The variations, to a great extent, are likely related to the baseline, which is dependent on driver, payloads, and routes.

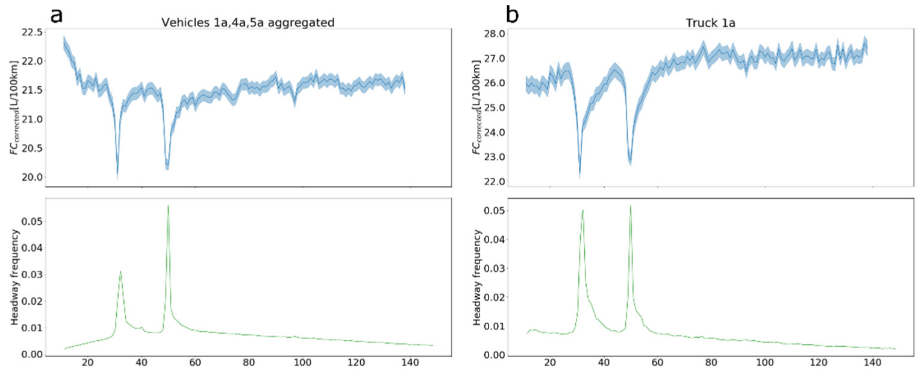

Figure 7 – Corrected fuel consumption and headway frequency distribution for the vehicles without air pressure system installed. Both panels a) - b): on top in dark blue the mean fuel consumption and the standard error (shaded area). The bottom plot in green shows the headway distance density distribution. a) shows the data for the Trucks 1a, 4a, 4b, 5a and 5b together whereas panel b) shows the data for Truck 1a only. Truck 1a had the most equally distributed headway frequency between 33 and 50 m.

In Figure 7 we also show the corrected fuel consumption for Truck 1a only (Figure 7 b). Truck 1a had the most equally distributed headway frequency between 33 and 50 m, i.e. the most equal distribution between time spent at 33 m and 50 m. However, Figure 7 b) shows that Truck 1a has an unusually high reduction in corrected fuel consumption due to ACC use (around 4 litres). For this truck, the difference in reduction from 50 m to 33 m was around 2%.

2.4.3 *Change in fuel consumption with the headway*

The pressure differences with the headway (as shown in the lower panels of Figure 5 and Figure 6) give an estimate of the fuel consumption variation with headway alone. The change in pressure is most notable between 30 metres and 10 metres headway. The observed drop in air pressure of 50-100 Pa can be associated with changes in the air drag of 150 to 300 Newtons, based on an effective frontal area of 3 m^2. The effective frontal area is roughly related to the C_d*A in aerodynamics, where the frontal area is A = w * h = 2.4 * 3.4 = 8.16 m^2. The force difference due to the drop in air pressure is roughly related to 1 to 2 litres per 100 km reduction in fuel consumption, for the shortest headway of 10 metres.

Sharp drops in air pressure are also observed at distances corresponding to the use of ACC. This seems to suggest that the lower air drag is, in part, related to the stable air flow conditions in the convoying situation. The effect on the pressure of ACC, at the same headway, is about a quarter of the effect of reducing the distance to 10 metres headway. More appropriately, in normal use, the use of ACC appears to reduce air drag as much as a decrease in headway of 10 metres.

From the pressure measurements it may be concluded that a short headway (shorter than the settings of the different ACC modes) would reduce air drag further. However, the corrected fuel consumption at these short distances does not show the reductions expected from this decrease in pressure. I.e. based on Figure 5 (risky) tailgating at short distances does not result in fuel consumption reductions equal to those achieved when ACC is used.

It is therefore estimated that if the headway can be reduced to 10 metres, *in combination with an ACC mode*, the fuel consumption reduction can be about 2 litres per 100 km, as compared to a headway of 70 metres or more. This is based on the force exerted on the front of the cabin, as measured by the pressure sensor. The pressure sensor gives a proper indication of the variation of the air drag with the distance. It must however be noted that these results vary about a factor two in absolute levels. One truck, Truck 2b, has deviating results. If this vehicle is excluded the remaining variation in observed air drag is about 20%. This is probably related to the actual tractor and trailer aerodynamic configurations and wind conditions, or the placement of the pressure sensor on this truck, as absolute values are also lower than for the other trucks.

2.5 Conclusions

The impact of using ACC
To ensure that payload and driving dynamics do not bias conclusions about the use of ACC, the fuel consumption is corrected for these factors. The correlation between the *uncorrected* fuel consumption and ACC use is shown in Appendix A - 8.1.2 in Van Kempen et al. (2021). Clear decreases in the corrected fuel consumption are observed at distances associated with the ACC modes 1, 3 and 4. This reduction varies from 0.8 to 1.2 L/100 km, from the largest to the smallest headway.

Reduction due to different headway distances
Given a typical fuel consumption of 22 L/100km for constant velocity on the motorway, the *average* fuel consumption reduction is 4.3 to 5.6% from 50 metres to 33 metres headway. ACC driving is more fuel efficient than when ACC is switched off in the control condition, or at distances not associated with the relevant ACC mode. The real-world data does show a spread in the results when comparing the fuel savings of the individual trucks; for the 50 metres headway (ACC 3) this ranges from 3.3-5.5% and for a 33 metres headway (ACC 1) this ranges from 3.0-5.7%. The variations, to a great extent, are likely related to the baseline, which is dependent on driver, payloads, and routes.

Influence of planned convoys
Sharp drops in air pressure are observed at distances corresponding to the use of ACC. This seems to suggest that the lower air drag is, in part, related to the stable air flow conditions in the drafting/convoying situation. Pressure measurements suggest that a short headway (shorter than the settings of the different ACC modes) would reduce air drag further. It is estimated that if the headway can be reduced to 10 metres, in combination with an ACC mode, the fuel consumption reduction could be about 9% (2 litres per 100 km) as compared to not following another vehicle. Note that when comparing this to a headway of 33 metres (ACC 1), the fuel consumption reduction could be about 4%.

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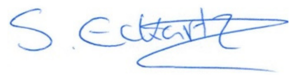
4 Signature

The Hague, 20 December 2021



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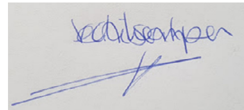

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