Effects of Semi-trailer Modifications on HGV Fuel Consumption

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Abstract

This article investigates the effects of aerodynamic and lightweight double-deck semi-trailers on fuel consumption of Heavy Goods Vehicles (HGVs). The HGVs were evaluated using in-service data, and computer-based simulations with coefficients of aerodynamic drag and rolling resistance estimated from coast-down tests conducted on a test track. The coast-down tests showed that the aerodynamic features reduced the coefficient of aerodynamic drag by approximately 7.2% and the wide single tyres on the lightweight trailers reduced the coefficient of rolling resistance by approximately 10%. The in-service data showed that the aerodynamic features on the aerodynamic vehicles have a statistical significance on fuel consumption. Computer-based simulations showed that the aerodynamic-lightweight trailer reduces the HGV's fuel consumption by approximately 20.2% for a long-haul drive cycle. As these improvements don't have significant barrier to implementation, which is the case with electrification of HGVs, fleet operators can employ these improvements to reduce their carbon emissions.

Keywords: Double-deck semi-trailers; heavy goods vehicle; fuel consumption; coast-down test.

1. Introduction

There are numerous technological opportunities in the short to medium term to improve the fuel efficiency of Heavy Goods Vehicles (HGVs) (Delgado et al., 2017). While tractors are often the focus of research and development into fuel efficiency technologies, trailers are generally considered as an afterthought due to their relatively low cost. Trailers play a vital role in road freight transport (McKinnon, 2006) and should be included in strategies to reduce the carbon emissions produced by the sector (Galos et al., 2015). Broadly speaking, three main technologies are available to reduce fuel consumption of trailers: low rolling resistance tyres, aerodynamic packages to reduce drag, and light-weighting using new and alternative materials to reduce mass and increase payload (Greening et al., 2015).

Aerodynamic drag is a significant component of energy consumption, particularly in long haul operations due to the high average speeds (Zhao et al., 2013; Lajunen, 2014). The aerodynamic drag is dependent on

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the design of the tractor and trailer, and the interaction between them. In (Wood and Bauer, 2003), the four primary sources of aerodynamic drag and their respective percentage contributions for a tractor-trailer are outlined: the tractor front (25%), the gap between the tractor-trailer (20%), the trailer's underbody (30%), and the rear of the trailer (25%). Due to the considerable difference in tractor and trailer bodies in North-America and the UK, e.g. long-nose tractor and variable tractor-trailer gap in North-American HGVs are not present in HGVs in the UK, the potential contributions can be different for HGVs in the UK. Nevertheless, a variety of technology packages are available to reduce the drag across all these sources. They include streamlining the shape of the tractor and trailer, adding side panels and fairings, and even complete redesigns which could theoretically reduce the drag coefficient by 42% in the long-term (Delgado et al., 2017). Note, however, that any reduction in payload due to changing the shape can have a negative effect on overal energy consumption. So such large drag reductions are not necessarily beneficial to reduce carbon emissions. This effect may happen in transport operations where the trailer is fully filled by volume before reaching its mass limit.

The average tractor weight increased over the last 20 years due to factors such as safety and comfort requirements, and the increasing stringency of pollutant emission standards (Hill et al., 2015). This trend highlights the need to reduce the mass of the tractor-trailer combination where possible in order to further increase the payload. Reducing the trailer's unladen mass is one of the most straightforward vehicle design changes that can be made (Odhams et al., 2010). The most practical area for manufacturers to reduce trailer mass in the short-term is by using lightweight composites for trailer decking and side walls, and the design of the frame. In the long-term more radical changes are possible to significantly reduce trailer weight (Galos and Sutcliffe, 2019). For example, a composite chassis formed of carbon fibre reinforced polymer beams and a pultruded glass fibre reinforced polymer deck could drastically reduce overall trailer weight by up to 1326 kg (Galos and Sutcliffe, 2019). However, the materials are not yet affordable. In (Hill et al., 2015), the overall potential of light-weighting to reduce the emissions of heavy duty transport vehicles was examined. The results showed that it is possible to achieve mass reductions of 5% in the short-term and 17% by 2030.

In (Galos et al., 2015), a study was carried out in the UK to assess the potential for improving trailer design through light-weighting. It found a particularly attractive opportunity for double-deck trailer operations. Their analysis of loaded double-deck trailers for a UK grocery fleet operator found the average number of cages transported per trailer was only 83% of the maximum allowable 75 cages, due to reaching the axle load limit. Their analysis highlights the opportunity to improve the payload capacity by light-weighting the trailer. This paper focuses on evaluating a trial of new Lightweight and Aerodynamic Double Deck (LADD) trailers developed through the Low Emissions Freight Trial (TRL).

During the project, 2 aerodynamic trailers, 2 lightweight trailers and 2 aerodynamic-lightweight trailers were manufactured. All of them were double-deck semi-trailers, meant for long haul transport operations. These trailers were then operated by a supermarket chain for transport operations between their distribution centres and outlets. The main project objective was to evaluate the fuel consumption of the prototype vehicles against baseline HGVs. Both the prototype and baseline HGVs were tractor semi-trailer combinations. This article shares the analysis from this project, including coast-down tests to estimate the reduction in coefficient of aerodynamic drag from the aerodynamic features and the reduction in coefficient of rolling resistance from the use of wide single tyres, instead of dual pairs, on the lightweight trailers.

The main contributions of this article are as follows:

- Estimation of coefficients of aerodynamic drag and rolling resistance of the double-deck HGVs.
- Evaluation of the double-deck HGVs for in-service drive cycles using telematics data.
- Model-based evaluation of the double-deck HGVs for standard drive cycles and different vehicle weights.

The in-service evaluation used telematics data, whereas the evaluation for standard drive cycles used model-based simulations with experimentally estimated coefficients of aerodynamic drag and rolling resistance. The coast-down experiments to estimate these coefficients were conducted on a test track.

2. Aerodynamic and Lightweight Semi-trailers

The aerodynamic features on the aerodynamic HGVs and aerodynamic-lightweight HGVs reduced their aerodynamic drag. These features are shown in Fig. 1. The semi-trailers are 13.58 m long and 2.55 m wide.

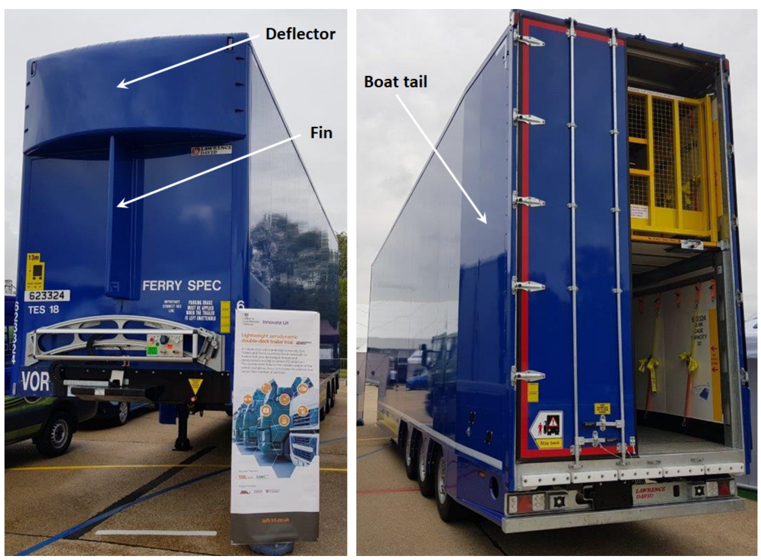


Figure 1: The semi-trailer aerodynamic features: boat tail, deflector and fin.

At the rear end of the trailer, there is a tapered 1.48 m long ‘boat tail’ at an angle of 4.5 deg. The boat-tailing was only applied to the sides of the trailer, as can be inferred from Fig. 1. It was not applied to the trailer top to avoid undesired loading issues, which may result in undesired transportation efficiency. Wind tunnel tests on a $\frac{1}{10}^{th}$ scale model (Garcia et al., 2018) showed approximately 3.4% reduction in the coefficient of aerodynamic drag due to this modification. Although a larger taper (up to 9 deg) would have been more beneficial, the angle was constrained by the necessary width of the rear doors. The front end of the trailer has a deflector and fin to prevent cross flow due to side winds. These showed approximately 2.5% and 2.4% reductions in drag, respectively, in the wind tunnel tests. Note that the type of tractor used in this work, which is shown in Fig. 3, and the scale model used in the wind tunnel tests have the same aerodynamic features, including the roof deflector, side extenders and tractor-trailer gap. Together, all three aerodynamic features reduced the aerodynamic drag by approximately 8%. The project and baseline trailers were fitted with full-length side skirts, optimised to reduce underbody flow and hence drag. The 8% drag reduction is in addition to the performance improvement from the side skirts.

The trailer mass was reduced by using lighter materials for the chassis, lower and upper decks, doors, running gear, and for the side-walls of the semi-trailer. The light-weighting features included high strength steel rolling chassis, and composite materials for the upper and lower decks. The lightweight trailers were fitted with wide single tyres, which lowered the coefficient of rolling resistance compared to the dual pairs. The prototype light-weight trailer had a mass of 8.8 t compared to the baseline mass of 11.3 t, i.e. a reduction of 2.5 t. However, shortly after commencing transport operations, the trailer decks and side-walls developed defects. Therefore, these parts need reinforcement and this activity is ongoing. This work used the proven mass reduction of 1350 kg from the chassis. From previous research (Galos and Sutcliffe, 2019), a proposed mass reduction of 500 kg from the side-walls, 120 kg from the decks and 40 kg from the doors were also used.

3. Methodology

This section describes the data collection and evaluation methods, and the types of vehicles used in each evaluation method. Telematics data from two aerodynamic HGVs and a baseline HGV were collected for a period of 5 months, while these vehicles performed their normal transport operations. This data was used to perform an in-service analysis of these vehicles to understand the benefits of the aerodynamic HGVs for their normal transport operations.

Table 1: Coefficients of aerodynamic drag times frontal area (C_dA), coefficients of rolling resistance (C_r) and UVWs of different vehicle types.

HGV type	C_dA [m^2]	C_r [-]	UVW [t]
Baseline	8.45	0.0050	19.566
Aerodynamic	7.84	0.0050	19.566
Lightweight	8.45	0.0045	17.556
Aerodynamic-lightweight	7.84	0.0045	17.556
Lower Rolling Resistance	8.45	0.0045	19.566
Lower UVW	8.45	0.0050	17.556

The analysis of telematics data has limitations arising from numerous factors, including different wind velocities, road slope profiles and route profiles. In addition, telematics data was not available for the lightweight vehicles. Therefore, model-based evaluations were also performed to analyse performance of the HGVs. This analysis was performed for the baseline HGV, aerodynamic HGV, lightweight HGV, aerodynamic-lightweight HGV, HGV with lower rolling-resistance and HGV with lower Unladen Vehicle Weight (UVW). Note that the lightweight HGVs have lower rolling-resistance and UVW. Table 1 shows the parameters of each vehicle type. The model-based evaluations were performed for six drive cycles, and they used coefficients of aerodynamic drag and rolling resistance, which were estimated using coast-down experiments conducted on a test track.

4. Data Collection

This section describes data collection from the telematics system and coast-down tests. The telematics data were collected in-service, whereas the coast-down tests were performed on a test track.

4.1. Telematics Data

Telematics data from two tractors, each pulling an aerodynamic double-deck semi-trailer, and from a tractor, pulling a baseline double-deck semi-trailer, were collected in-service for a period of 5 months in 2019. All three tractors were of the same model and make, 'MB Actros 2545' from Daimler Truck AG, and were fitted with telematics systems from Daimler Fleetboard GmbH. The telematics data set included date (yyy:mm:dd), average speed (km/h), diesel used (l), transport work (t.km), distance (km), driving style, operational time (hh:mm:ss), vehicle start time (hh:mm:ss) and vehicle stop time (hh:mm:ss), at a frequency of once per day. Here, driving style is a driver performance variable out of 1000, and it depends on the acceleration and deceleration values.

4.2. Coast-down Tests

Coast-down tests were conducted to estimate the coefficients of aerodynamic drag and rolling resistance of an HGV with an aerodynamic-lightweight double-deck semi-trailer and of an HGV with a baseline double-deck semi-trailer. These tests were carried out on the twin-straights test track at Horiba-MIRA Ltd, UK, shown in Fig. 2. In each direction, the horizontal track is 1.6 km long and the two straights are joined by banked loops at each end.

These tests had two objectives: 1) estimate the reduction in coefficient of aerodynamic drag due to the aerodynamic features of the aerodynamic trailers, and 2) estimate the reduction in coefficient of rolling resistance due to the wide single tyres on the lightweight trailers. The reduction in coefficient of aerodynamic drag is applicable for the aerodynamic HGVs and the aerodynamic-lightweight HGVs. The reduction in coefficient of rolling resistance is applicable for the lightweight HGVs and aerodynamic-lightweight HGVs.

The HGVs were instrumented with an inertial and navigation system, 'RT3022', from Oxford Technical Solutions Ltd. The processing unit with a built-in inertial measurement system was installed inside the tractor cabin. The primary GPS antenna was installed on the tractor roof. Before each test, the 'RT3022' was initialised using the manufacturer instructions.

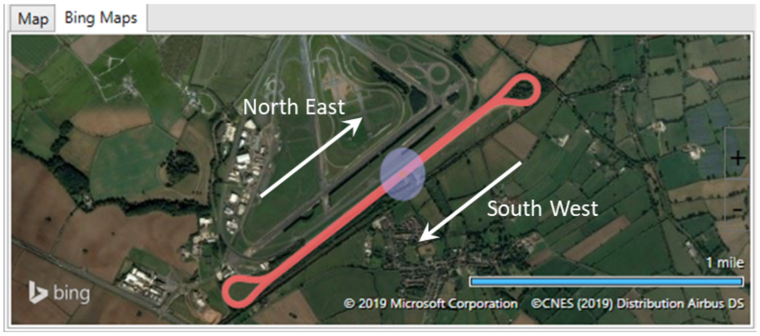


Figure 2: Satellite image of the twin-straights test track at Horiba-MIRA Ltd, UK, where the coast-down tests were performed.

Figure 3: A photograph of the instrumented baseline heavy goods vehicle.

The coast-down tests were performed with an unloaded trailer and with an almost fully loaded trailer. When loaded, the trailer was loaded with concrete blocks to a Gross Vehicle Weight (GVW) between 43 and 44 t. The GVW was measured using the weighing bridge at the test facility.

During each test, the HGV was accelerated to a maximum speed close to 84 km/h and was allowed to coast-down. As the twin-straights test track is only 1.6 km long in each direction, it is not long enough for the HGV to coast-down from 84 km/h to standstill in one go. Therefore, when the vehicle approached the end of a straight segment, the final vehicle speed was noted. The vehicle was brought back to the start of the same straight segment with a slightly higher speed than the noted final speed from the last coast-down lap. This process was continued until the vehicle stopped. This whole process was done for both directions of travel along the twin-straights test track, i.e. North East and South West in Fig. 2. The track is very close to level with no measurable change of elevation between the two ends. Fig. 4 shows the longitudinal vehicle speed profile during one of the coast-down tests. In addition to the vehicle's longitudinal speed, longitudinal acceleration was measured.

The longitudinal equations of motion of a vehicle (Madhusudhanan et al., 2020; Hunt et al., 2011) is as

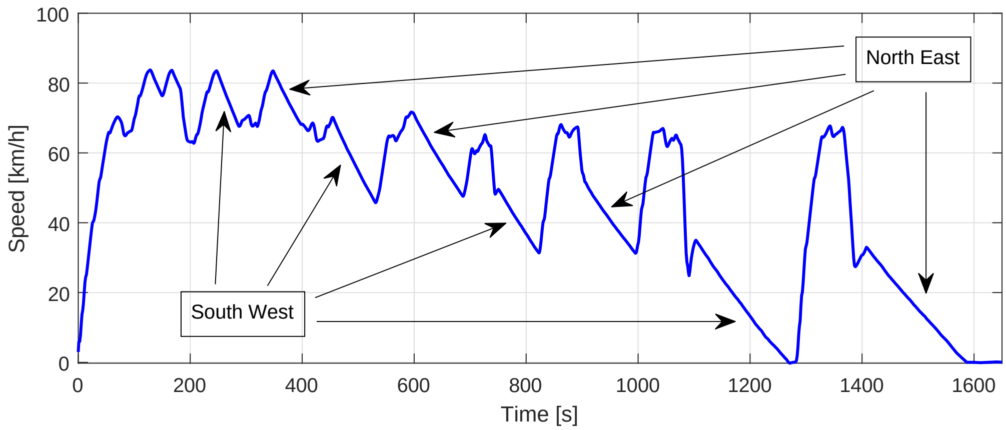


Figure 4: A typical example of the measured speed profile from one of the coast-down tests.

follows:

$$
\begin{aligned}
P_w(t) &= ma(t)v(t) + P_a(t) + P_r(t) + P_g(t) && (1) \\
P_a(t) &= \frac{1}{2}\rho_{air} C_d A \left(v(t) - v_w\right)^2 v(t) && (2) \\
P_r(t) &= C_r mgv(t) && (3) \\
P_g(t) &= mg \sin\theta(t) v(t) && (4)
\end{aligned}
$$

Here P_w is the engine power transmitted to the wheels, m is the gross vehicle mass, a is the longitudinal acceleration, v is the longitudinal speed, P_a is the power dissipated by aerodynamic drag, P_r is the power dissipated by rolling resistance, P_g is the power required to ascend the road gradient, $\rho_{air} = 1.225$ kg/m^3 is the density of air, C_d is the coefficient of aerodynamic drag, A is the vehicle's frontal area, v_w is the component of the wind speed along the South West direction in Fig. 2, C_r is the coefficient of rolling resistance, $g = 9.81$ m/s^2 is the acceleration due to gravity and θ is the road gradient. The effective mass of rotating components, driveline mechanical losses and speed dependence of rolling resistance coefficient McAuliffe and Chuang (2016), were ignored while estimating the coefficients. Although these are drawbacks of the estimation method, their effects were assumed negligible to compare two vehicles with the coefficients obtained using the estimation method used in this work.

When a vehicle coasts-down on a horizontal road, $P_w = 0$ as the vehicle is in neutral gear and $P_g = 0$ as the road gradient is zero. Therefore, Equation (1) can be simplified as follows:

$$ma(t) = -\frac{1}{2}\rho_{air} C_d A \left(v(t) - v_w\right)^2 - C_r mg \tag{5}$$

Estimation of the coefficient of aerodynamic drag, C_d, and the coefficient of rolling resistance, C_r, involved two steps: 1) estimation of the wind speed, v_w, and 2) estimation of the coefficients.

For the first step, Equation (5) was rewritten as follows:

$$a(t) = -\frac{1}{2m}\rho_{air}C_dA\left(v(t)-v_w\right)^2 - C_rg \tag{6}$$

$$= \begin{bmatrix} -\frac{1}{2m}\rho_{air}C_dA & -C_rg \end{bmatrix}\begin{bmatrix} \left(v(t)-v_w\right)^2 \\ 1 \end{bmatrix} \tag{7}$$

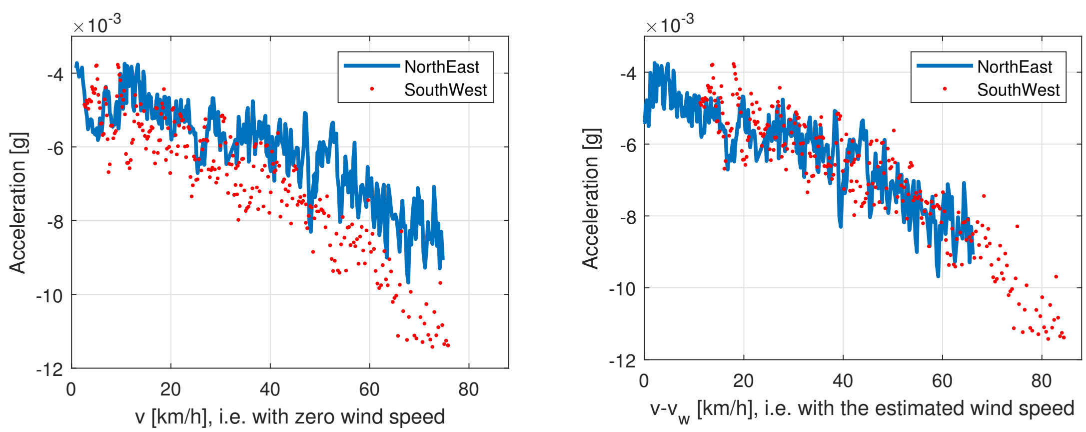
$$= C^T\begin{bmatrix} \left(v(t)-v_w\right)^2 \\ 1 \end{bmatrix} \tag{8}$$

Here $C = \begin{bmatrix} -\frac{1}{2m}\rho_{air}C_dA & -C_rg \end{bmatrix}^T$ is the coefficient vector. Using the model form in Equation 8, the coefficient vector, C, can be estimated so that a linear model relating $\left(v(t)-v_w\right)^2$ and $a(t)$ can be found. This linear model fitting was used in the following optimisation problem to estimate the wind speed:

$$\hat{v}_w = \underset{x \text{ s.t. } -10 \leq x \leq 10}{\text{argmin}} \sum_{i=1}^{2} \frac{\left[C_{NE}(i,x) - C_{SW}(i,x)\right]^2}{C_{SW}^2(i,x)} \tag{9}$$

Here, x is the optimisation argument whose optimised value is the wind speed estimate, $\hat{v}_w$; $C_{SW}(x) \in R^2$ is the coefficient vector of the linear model that fits $\left(v_{SW}(t)-x\right)^2$ and $a_{SW}(t)$ as shown in Equation (8); $C_{NE}(x) \in R^2$ is the coefficient vector of the linear model that fits $\left(v_{NE}(t)+x\right)^2$ and $a_{NE}(t)$; v_{NE} and v_{SW} are the speed measurements when the vehicle coasts-down in the North East and South West track respectively; and a_{NE} and a_{SW} are the acceleration measurements when the vehicle coasts-down in the North East and South West track respectively.

The vehicle speed and acceleration measurements were sampled at 1 kHz, and a moving average filter with a window size of 200 was used to improve the signal to noise ratio.



(a) Without wind speed correction. (b) With wind speed correction.

Figure 5: Vehicle's $v(t) - v_w$ versus $a(t)$ without and with wind speed correction with the wind speed estimate of -2.4 m/s.

Fig. 5 shows the $v(t) - v_w$ versus acceleration, i.e. $a(t)$, with zero wind speed and the estimated wind speed value. These plots are from two tests. The North East plots only use measurements when the vehicle coasted-down along the North East direction, and the South West plots only use measurements when the vehicle coasted-down along the South West direction. These plots correspond to the quadratic equation relating $v(t) - v_w$ and $a(t)$ in (6). Note that crosswinds can affect the coefficient of aerodynamic drag Hucho (1986). Therefore, the cost-down tests were conducted when the wind speed was minimal, given the practical constraints such as available track time. The average wind speed during these tests was 1.1 m/s with a maximum of 2.4 m/s and minimum of 0.5 m/s. Therefore, the effect of crosswind was assumed to be negligible. If this assumption is valid, and if the wind speed is therefore estimated appropriately, the North East and South West plots should overlap each other. In the right hand plot, with the estimated wind speed of -2.4 m/s, the North East and South West plots overlap.

After estimating the wind speed, the second step was performed, i.e. estimation of the coefficients of aerodynamic drag and rolling resistance. Using the wind speed estimate from Equation (9), the coefficients were initialised with the following values:

$$[C_d A]_0 = -\frac{m\left[C_{NE}(1, \hat{v}_w) + C_{SW}(1, \hat{v}_w)\right]}{\rho_{air}} \tag{10}$$

$$[C_r]_0 = -\frac{C_{NE}(2, \hat{v}_w) + C_{SW}(2, \hat{v}_w)}{2g} \tag{11}$$

Here, $[C_d A]_0$ is the initial estimate of the coefficient of aerodynamic drag times frontal area, and $[C_r]_0$ is the initial estimate of the coefficient of rolling resistance. The product, $C_d A$, was estimated as a single quantity as it is difficult to estimate the effective frontal area due to the complicated shape of a tractor semi-trailer combination.

Based on the range of values of these coefficients from literature, constraints, 5 m$^2 \leq C_d A \leq 12$ m^2 and $0.002 \leq C_r \leq 0.009$, were set. These allowable ranges were set as follows:

$$Pz \leq b \text{ where} \tag{12}$$

$$P = \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix} \tag{13}$$

$$b = \begin{bmatrix} 12 \\ -5 \\ 0.009 \\ -0.002 \end{bmatrix} \text{ and} \tag{14}$$

$$z = \begin{bmatrix} C_d A & C_r \end{bmatrix}^T \tag{15}$$

The coefficients, $\hat{z}$. were found by minimising the difference between the measured time, t_m, the vehicle took to coast-down from v_0 to standstill on the test track and the time estimate, $\hat{t}$, for the vehicle to coast-down from v_0 to standstill with the optimisation argument, z.

$$\hat{z} = \underset{z \text{ s.t. } Pz \leq b}{\operatorname{argmin}} \left[t_m - \hat{t}(z, v_0, \hat{v}_w, m)\right]^2 \tag{16}$$

$\hat{t}$ was calculated by integrating Equation (5) according to:

$$\hat{t}(z, v_0, \hat{v}_w, m) = t \text{ s.t. } \int_0^t \left[-\frac{\rho_{air}(v(t)-\hat{v}_w)^2}{2m} \quad -g\right] x \; dt = 0 \text{ with} \tag{17}$$

$$v(0) = v_0 \tag{18}$$

The optimisation uses the initial estimates from Equations (10) and (11), and the constraints in Equation (12). It was run until the relative changes in all elements of the optimisaiton argument were less than the step tolerance of 10^{-10}. Fig. 6 shows the measured speed profile from one of the tests and the modelled speed profile using Equation (6) with the estimated coefficients of aerodynamic drag and rolling resistance, and wind speed.

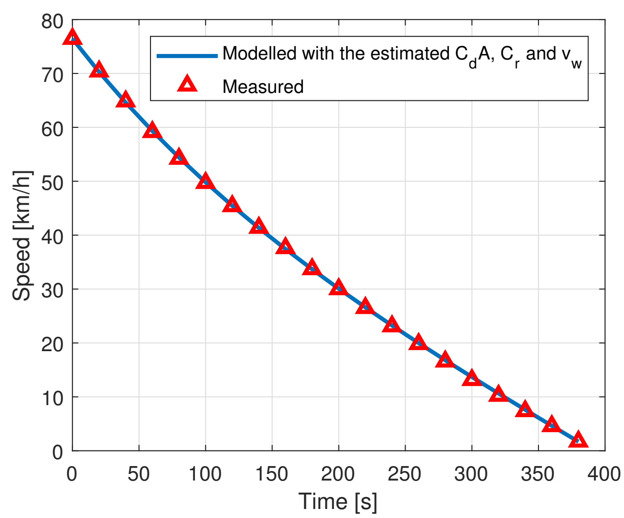


Figure 6: Measured speed from one of the coast-down tests and modelled speed using the estimated coefficients and wind speed.

Table 2: Results of the coast-down tests of an aerodynamic-lightweight (AL) HGV and a baseline (BL) HGV. SD stands for standard deviation.

Test	C_dA - BL $[m^2]$	C_dA - AL $[m^2]$	C_r - BL [-]	C_r - AL [-]
Test 1 South West	8.38	7.81	0.0052	0.0047
Test 2 North East	8.41	7.85	0.0051	0.0045
Test 3 South West	8.41	7.79	0.0049	0.0045
Test 4 North East	8.51	7.88	0.0048	0.0044
Test 5 South West	8.54	7.95	0.0051	0.0046
Test 6 North East	8.43	7.77	0.0046	0.0041
Mean $\pm$ SD	8.45 ± 0.06	7.84 ± 0.07	0.0050 ± 0.00023	0.0045 ± 0.00021

The coast-down test procedure, described above, was employed for an aerodynamic-lightweight HGV and a baseline HGV. For each vehicle, 3 tests were conducted on the North East test track and 3 on the South

West test track. Table 2 shows the estimated coefficients of aerodynamic drag and rolling resistance from the coast-down tests.

From Table 2, it is seen that the aerodynamic features reduced the coefficient of aerodynamic drag by approximately 7.2% and the wide single tyres on the lightweight trailer reduced the coefficient of rolling resistance by approximately 10%. Considering the model assumptions regarding the effective mass of rotating components, driveline mechanical losses, crosswind and speed dependence of coefficient of rolling resistance, the estimated coefficients are sufficiently reliable that the relative results of one vehicle configuration to another should be reliable. In addition, the reduction in aerodynamic drag is comparable to the 8% reduction, observed in the scaled down wind tunnel tests, mentioned in Section 2.

5. Evaluation of the HGVs for Transport Performance and Cost

This section shares the evaluation results of different vehicle types for different drive cycles. First, in-service telematics data was used to compare 2 HGVs with aerodynamic trailers with a baseline vehicle. Next, the fuel consumption models were used to evaluate an aerodynamic trailer, a lightweight trailer, an aerodynamic-lightweight trailer and the baseline trailer. The drive cycles used in the model-based evaluation are long haul, regional delivery, urban delivery and city centre drive cycles from the Low Carbon Vehicle Partnership (LowCVP) (Robinson and Eastlake, 2016), heavy heavy-duty diesel truck (HHDDT) cruise drive cycle (DieselNet), and motorway cruising at 84 km/h. These drive cycles represent different driving scenarios an HGV may encounter. The LowCVP long haul and HHDDT cruise drive cycles represent typical scenarios an HGV may encounter while performing a long haul transport operation. The LowCVP urban delivery and city centre drive cycles represent typical scenarios in an urban setting with more acceleration and deceleration events than the long haul drive cycles. The HHDDT drive cycle is based on the HHDDT chassis dynamometer test, developed by the California Air Resources Board and West Virginia University.

5.1. Telematics Data

A statistical analysis was performed to understand whether the *trailer type*, i.e. baseline or aerodynamic, has a statistically significant effect on fuel consumption. This analysis was only performed for the aerodynamic and baseline vehicles. After discarding unwanted data sets such as those with daily distance less than 100 km, which account for 0.5% of the total vehicle kilometres, a multiple linear regression model of the following form was fitted to the telematics data:

$$f = \beta_0 + \beta_1 \bar{m} + \beta_2 \bar{v} + \beta_3 s + \beta_4 T \qquad (19)$$

Here, f is the fuel consumption in l/km, β_0 to β_4 are the model coefficients, $\bar{m}$ is the daily average vehicle mass in tonne, $\bar{v}$ is the daily average vehicle speed in km/h and s is a driver performance variable out of 1000, which is calculated by the telematics provider and depends on acceleration and deceleration values. If $s = 1000$, the driver performance is maximum, i.e. a smooth driver. In (19), $\bar{m}$, $\bar{v}$ and s are numerical predictor variables, whereas the trailer type, T, is a categorical predictor variable. Outputs from the analysis include the coefficients expressing the change in fuel consumption for unit changes in the predictor variables, the estimated standard error (SE) in these coefficients, and the p-value expressing the probability that the null-hypothesis related to this statistic can be rejected. In this analysis, the null-hypothesis was rejected (i.e. statistical significance was assumed) for a p-value less than 0.05.

Table 3: Results of the multiple linear regression model fit using the telematics data.

Variable	Coefficient (β)	Unit	Standard Error	p-value
Intercept	0.3265	l/km	0.0128	< 0.00001
mass ($\bar{m}$)	0.0044	l/t.km	0.00028	< 0.00001
speed ($\bar{v}$)	-0.0014	lh/km^2	0.00018	< 0.00001
driving style (s)	-0.00013	l/km	1.11×10^{-5}	< 0.00001
trailer type (T)	-0.0068	l/km	0.0018	0.00016

Results of the model fit for the predictor variables are shown in Table 3. The results show that fuel consumption increases with increasing vehicle weight, reducing speed and lower driver performance, with high statistical significance. The effect of trailer type is also statistically significant with a p-value of 0.00016. The negative sign in the coefficient of trailer type denotes a reduction in fuel consumption for the aerodynamic trailer compared with the baseline trailer.

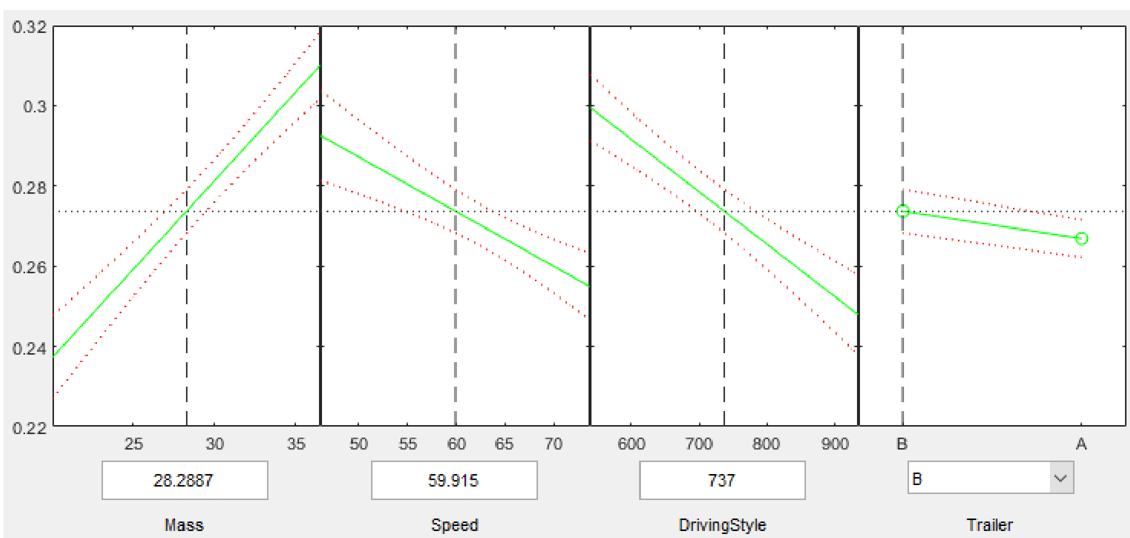


Figure 7: Predictor slice plots showing best-fit model predictions and 95% confidence limits.Y-axis: fuel consumption [l/km]. Subplots: Average vehicle mass [t], Average speed [km/h], Driving style [-], Trailer type (B=Baseline, A=Aerodynamic).

Figure 7 illustrates predictions by the model, showing the effect of the four predictor variables for given values of the other three variables (as indicated below the sub-plots). The red dashed lines are the 95 % confidence bounds on the model. Of note is the counter-intuitive result that the fuel consumption decreases with increasing average speed, which is mostly caused by the lower traffic congestion with higher average speed Nasir et al. (2014); Zhang et al. (2011). The increase in fuel consumption with lower driver performance is caused by frequent or harsh acceleration or deceleration events Meseguer et al. (2015, 2017). The analysis show that the aerodynamic HGV's fuel consumption is approximately 2.5% lower for the operating conditions in Fig. 7 (i.e. $\bar{m} = 28.3$ t, $\bar{v} = 59.9$ km/h and $s = 737$).

This analysis of telematics data has limitations arising from numerous factors, including different wind velocities, road slope profiles and route profiles. Therefore, model-based evaluations were also performed to analyse performance of the HGVs.

5.2. Model-based Evaluation

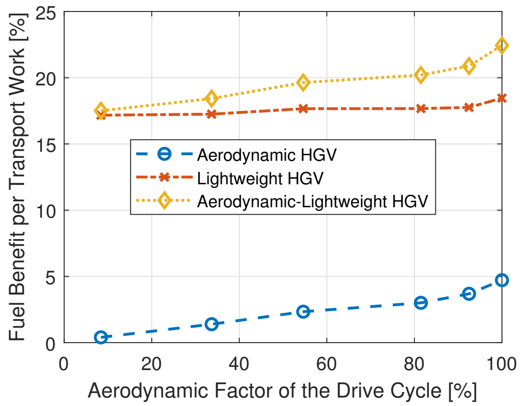
The model used to evaluate fuel consumption was based on previous research on fuel consumption modelling (Hunt et al., 2011; Madhusudhanan et al., 2020). For all the vehicle types that were manufactured during this project, i.e. aerodynamic HGV, lightweight HGV, aerodynamic-lightweight HGV and baseline HGV, fuel consumption models were created with the coefficients of aerodynamic drag and rolling resistance from the coast-down tests. The lightweight HGVs were fitted with lower rolling resistance tyres. To differentiate the effects of lower rolling resistance and light-weighting, two more vehicle types, i.e. one with lower rolling resistance and the other with lower Unladen Vehicle Weight (UVW), were evaluated. Table 1 shows the coefficients and UVWs of different vehicles.

The drive cycles used in the model-based evaluation, and their details are shown in Table 4. The 'aerodynamic factor' in Table 4 is the normalised ratio of energy required to overcome aerodynamic drag versus the total energy required for the drive cycle. The aerodynamic factor was normalised using the ratio for motorway cruising at 84 km/h. Consequently, a score of 0 represents a low speed drive cycle in which aerodynamic drag is insignificant, whereas 100% represents steady speed operation at 84km/h on a motorway. The model-based evaluation used two GVW values: 1) 30.5 t, which was the average GVW from the telematics data of three HGVs from a period of 5 months, and 2) 44 t, which is the fully loaded case.

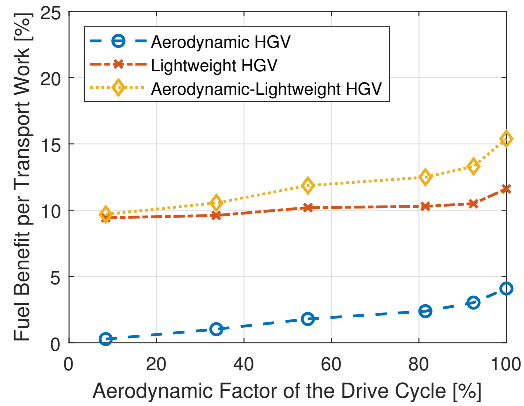
Table 4: Drive cycles used in the model-based evaluation of different HGVs.

Drive cycle	Average speed [km/h]	Duration [s]	Aerodynamic factor [%]
LowCVP City Centre	18.7	899	8.4
LowCVP Urban Delivery	43.7	656	33.7
LowCVP Regional Delivery	51.7	551	54.6
LowCVP Long Haul	72.9	1115	81.5
HHDDT Cruise	64.2	2083	92.5
Motorway Cruising at 84 km/h	84.0	1800	100.0

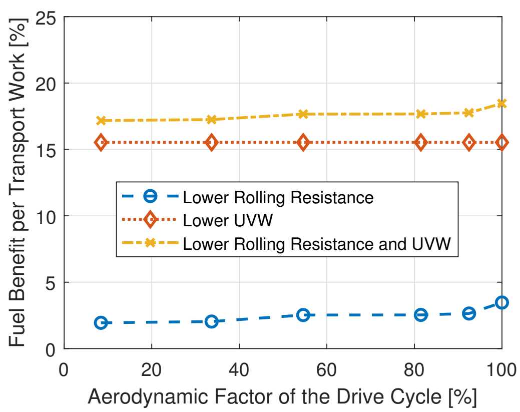
Fig. 8a to 8d show the percentage reduction in fuel consumption per t.km transport work of different vehicle configurations for the two GVW values. Here, t.km transport work is the work done to transport



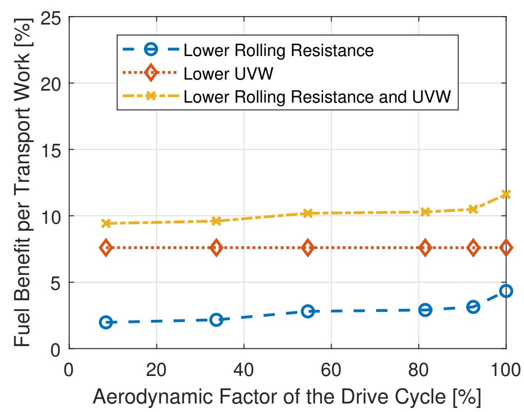
(a) For a GVW of 30.5 t, the average GVW from the telematics data.



(b) For a GVW of 44 t, which is the fully loaded case in the UK.



(c) For a GVW of 30.5 t, the average GVW from the telematics data. The 'Lower Rolling Resistance and UVW' case is the same as the 'Lightweight HGV' case in (a).



(d) For a GVW of 44 t, which is the fully loaded case in the UK. The 'Lower Rolling Resistance and UVW' case is the same as the 'Lightweight HGV' case in (b).

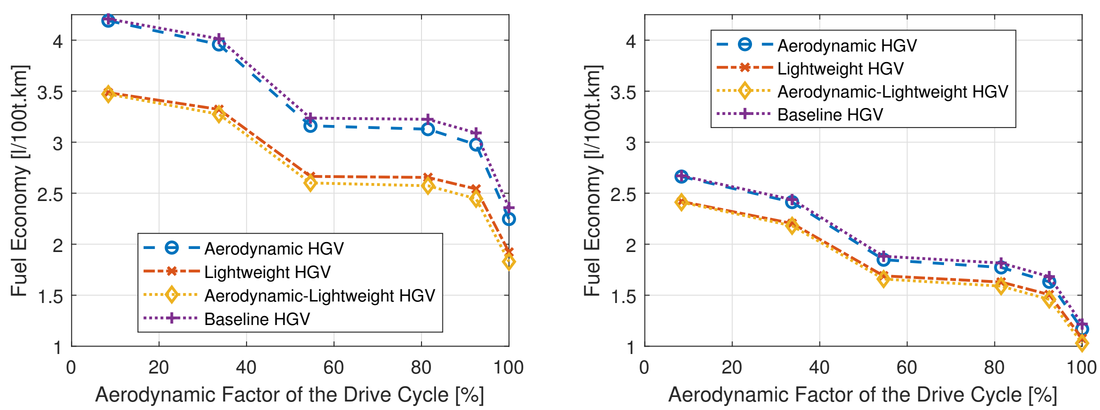
Figure 8: Fuel consumption benefit per t.km transport work [%] for different HGV configurations compared to the baseline.

1000 kg of goods for a distance of 1 km. The Aerodynamic HGV legend in Fig. 8a shows that the maximum fuel consumption benefit for the aerodynamic HGV is 4.7%, when it cruises on motorways at 84 km/h (aerodynamic factor of 100%). The second and third highest fuel consumption benefits, 3.7% and 3.0%, are for the HHDDT Cruise (a long haul drive cycle) and LowCVP Long Haul drive cycles, respectively. Clearly, the fuel consumption benefits would be greater if the cruising speed was higher. The benefit from aerodynamic features is the lowest for the LowCVP City Centre drive cycle due to frequent accelerations and decelerations, and lower speed values in the drive cycle.

The fuel consumption benefit for the Lightweight HGV in Fig. 8a is between 17.2% (LowCVP City Centre drive cycle) and 18.5% (Motorway Cruising at 84 km/h). The benefit of light-weighting depends on the mass reduction, which was assumed as 2010 kg in Section 2 with a proven mass reduction of 1350 kg from the chassis and a proposed mass reduction of 660 kg from the body. The results in Fig. 8c show that the wide single tyres with lower rolling resistance offer 1.9% (LowCVP City Centre drive cycle) to 3.5% (Motorway Cruising at 84 km/h) fuel consumption benefit, whereas the lower UVW offers 15.5% fuel consumption benefit. The 'Lower Rolling Resistance and UVW' cases in Fig. 8c and 8d are the same as the 'Lightweight HGV' cases in Fig. 8a and 8b, respectively.

The Aerodynamic-Lightweight HGV has the most fuel consumption benefit in Fig. 8a as it has aerodynamic and light-weighting features, and lower rolling resistance tyres. The fuel consumption benefit is the lowest for the LowCVP City Centre drive cycle at around 17.5% and is the highest for Motorway Cruising at 84 km/h at around 22.4%.

Comparing the results in Fig. 8a and 8b, and those in in Fig. 8c and 8d, indicates that the fuel consumption benefit per transport work decreases as the GVW increases.



(a) For a GVW of 30.5 t, the average GVW from the telematics data.

(b) For a GVW of 44 t, which is the fully loaded case in the UK.

Figure 9: Fuel consumption per transport work [l/100t.km] for different HGV configurations.

Fig. 9a and 9b show the fuel consumption per transport work [l/100t.km] of different vehicle configurations for the two GVW values. Contrary to Fig. 8a and 8b, Fig. 9a and 9b show that the fuel consumption per transport work [l/100t.km] decreases as the GVW increases. As shown in Fig. 9b, the lowest fuel consumption per transport work is for the fully loaded (44 t) Aerodynamic-Lightweight HGV.

Considering an average round trip distance of 240 km and 361 such trips in year (data from the project partner), and with a baseline fuel economy of 3.65 km/l (calculated from the telematics data), the baseline HGV needs approximately 23737 l of diesel per year. With a Net Calorific Value (NCV) of 35.99 MJ/l and Well-To-Wheel (WTW) equivalent carbon emission of 91.87 g/MJ for diesel UK-Government (2019); MacLeay et al. (2010), the baseline HGV's equivalent carbon emissions in a year is approximately 78.5 t. As the project partner's fleet consists of 724 double-deck semi-trailers, with 3% fuel benefit from the aerodynamic features in the long haul drive cycle, if the aerodynamic modifications were applied to all the fleet trailers, the equivalent carbon emission savings will be approximately 1705 t per year. Note that most double-deck trailers are operated for long haul transport operations. Similarly, with 21% fuel benefit from the aerodynamic-lightweight HGV for the long haul drive cycle, if the aerodynamic and light-weighting modifications were applied to all the fleet trailers, the equivalent carbon emission savings will be approximately 11935 t per year.

6. Conclusions

This article evaluated the effect of aerodynamic and lightweight interventions to double-deck semi-trailers on fuel consumption of HGV transport operations. The evaluation used in-service telematics data from 5 months, and predictions using simulation models. For the aerodynamic improvements, there is reasonable agreement between the estimated fuel consumption benefit from the model based analysis and from the telematics based analysis. The coefficients of aerodynamic drag and rolling resistance of different types of vehicle were estimated from the coast-down tests. Compared to a baseline trailer, the coast-down tests showed that the aerodynamic features reduced the coefficient of aerodynamic drag by approximately 7.2% and that the wide single tyres on the lightweight trailers reduced the coefficient of rolling resistance by approximately 10%.

The estimated coefficients were used in simulation model based evaluations to predict fuel consumption benefits. For a GVW of 30.5 tonne, the average GVW from the telematics data, the aerodynamic trailer reduces the HGV's fuel consumption by approximately 4.7% while cruising on UK motorways at 84 km/h and by approximately 3% on the LowCVP Long Haul drive cycle. The lightweight trailer reduces the HGV's fuel consumption by approximately 18.5% while cruising on motorways at 84 km/h and by approximately 17.7% on the LowCVP Long Haul drive cycle. The low rolling resistance tyres in the lightweight trailer offer approximately 3.5% fuel consumption benefit while cruising on motorways at 84 km/h and by approximately 2.5% on the LowCVP Long Haul drive cycle. The aerodynamic-lightweight trailer reduces the HGV's fuel consumption by approximately 22.4% while cruising on motorways at 84 km/h and by approximately 20.2% on the LowCVP Long Haul drive cycle. In addition, evaluations were performed for the LowCVP City Centre drive cycle, LowCVP regional delivery drive cycle, LowCVP urban delivery drive cycle and for the HHDDT cruise drive cycle. All three HGV configurations give the lowest fuel consumption benefit for the LowCVP City Centre drive cycle. The fuel consumption per transport work decreases as the GVW increases. The lowest fuel consumption per transport work is for the fully loaded (44 t) Aerodynamic-Lightweight HGV.

From the 5 months of telematics data from two aerodynamic HGVs and a baseline HGV, statistical significance with a p-value of 0.00016 was found for the effect of trailer type on fuel consumption. The results also showed statistical significance for higher fuel consumption with increasing vehicle weight, reducing speed and lower driver performance. The analysis show that the aerodynamic HGV's fuel consumption is approximately 2.5% lower than the baseline, which is similar to the model based results with mid-range aerodynamic factors.

From a policy and practice point of view, the results from this research imply that aerodynamic improvements of a semi-trailer can reduce fuel consumption for long-haul transport operations, whereas lightweighting a semi-trailer can reduce fuel consumption significantly in both long- and short-haul transport operations. As these improvements do not have significant barrier to implementation, which is the case with electricifation of HGVs and autonomous driving technologies like truck platooning, fleet operators can employ these improvements to reduce their carbon emissions.

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Data used in drafting of this article is available at: [[Details to be provided on acceptance of manuscript]].

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