EFFECTS OF PAYLOAD ON THE FUEL CONSUMPTION OF TRUCKS

RESEARCH FOR THE DEPARTMENT FOR TRANSPORT (DfT) FUNDED THROUGH THE DEPARTMENT FOR ENVIRONMENT FOOD AND RURAL AFFAIRS (DEFRA) AGGREGATES LEVY SUSTAINABILITY FUND (ALSF)

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1. EXECUTIVE SUMMARY

Increasing the gross weight at which a vehicle operates will increase its fuel consumption. Much less obvious is the precise relationship between payload and fuel economy. This research project set out to quantify that relationship in two types of operation: distribution, using articulated trucks at up to 44 tonnes gross combination weight (gcw); and tippers, using multi-axle rigids at up to 32 tonnes gross vehicle weight (gvw) and an articulated tipper at up to 44 tonnes gcw.

For the distribution trucks it was found that fuel consumption increased on average by 0.112 miles per gallon (mpg) for every tonne of payload added. For tipper trucks the results are less conclusive but one key finding is that a 44-tonner becomes more fuel efficient than a 32-tonner when payload exceeds 17 tonnes.

Other findings include these:-

Vehicles involved in any trials of this kind should always be checked first on a rolling-road dynamometer to ensure that their actual power and torque are established.

If analysis of the results is by journey leg, rather than by complete trip, then each leg has to be long enough to minimise the effect of rounding fuel consumption figures.

The relationship between payload and fuel consumption can be explained and modelled using linear regression, a statistical process. However, the number of records in the regression analysis needs to be high enough to produce accurate models. Regression models are sensitive to type of operation and the gross and unladen weights of the vehicles involved.

No direct relationship was found between engine horsepower and fuel consumption. Much more influential is complete powertrain specification (engine, gearbox and final drive). Journey time savings attributable to engine power output were small in this project.

Incorrect use or poor maintenance of a lift axle can have a big impact on fuel consumption.

2. INTRODUCTION

The stated overall aim of the project as set out in the specification was to "…simulate the full range of load conditions and measure the different fuel consumptions over repeatable but typical routes. Route one will be used for two articulated trucks, 40 and 44 tonne on 5 and six axles. Route two will be selected appropriate to test three tipper trucks: three and a four axle rigids and a 44 tonne articulated tipper."

To specify a vehicle that meets the necessary technical requirements and minimises whole-life costs, an operator needs impartial information. This report aims to provide just such information on the impact of payload on fuel consumption, and thus ultimately on operating costs. The two types of operation on which the research focuses are:

- A retail distribution operation involving a 4x2 tractor unit with tri-axle box-bodied semi-trailer and a 6x2 tractor unit with tri-axle box-bodied semi-trailer.

- A tipper (aggregates) operation involving a 6x4, 26-tonnes-gvw rigid tipper, an 8 x4, 32-tonnes-gvw rigid tipper, and a 6x2 tractor unit operating at 44 tonnes gcw with a tri-axle tipper semi-trailer.

Data collected have been used to produce charts showing how fuel consumption varies with payload. The implications of the data and the charts are discussed to draw out information of value to operators and to the Department for Transport.

Retail distribution vehicles typically go out carrying loaded roll cages as shown in Figure 1 and return empty or with empty roll cages. Sometimes collections are made from suppliers before returning to the distribution centre, in which case a vehicle could return heavier than when it left the depot.

Figure 1 Roll Cage

Source: Warehouse Equipment

Tipper vehicles on the other hand are typically loaded only one way, returning to a quarry or plant to collect and deliver the next load. They can make many deliveries per day and achieve a high level of customer service but forgo the opportunity to backload. So their operational profile is a combination of fully loaded and empty, although on some occasions a less than full load may be carried.

An opportunity arose in this research project to evaluate a 26-tonnes-gvw rigid tipper with a lifting rear axle (technically a 6 x 2). The vehicle was tested empty, with the axle up and down, but not on the same day as the other three tippers.

3. METHODOLOGY

Two articulated trucks, judged to be typical retail distribution fleet workhorses were used for one test. Rigid tipper trucks, together with one tractor unit and tipping semi-trailer, were used for the other test.

The methodology involved routes judged to be representative of these two types of operation with a slight bias towards toughness. For the retail distribution test the section-by-section fuel economy was recorded using data from in-cab displays.

Tipper vehicles typically travel much shorter distances in their normal work, raising the issue of accuracy for separate sections of a route. An in-cab display is accurate to only one decimal point, so when mpg is measured over a short distance the figure can be inaccurate. For example, where a vehicle travels 6.4 km (4 miles) and consumes 2.29 litres the true fuel consumption is 35.57 l/100 km (7.9mpg). But if the in-cab display shows 2.2 litres then the calculated fuel consumption would be 34.18 l/100 km (8.3mpg). This is why only fuel consumption figures for the entire route are used for the tipper tests.

The tipper vehicles all had side-mounted sheets which were used to seal the bodies when the vehicles were empty. This has been found to reduce aerodynamic resistance and improve fuel consumption (Wilcox, 1999) and is considered best practice.

To minimise the impact of variations in driver skills, all the vehicles were driven by instructors qualified under the SAFED (Safe and Fuel Efficient Driving) scheme. The instructors travelled the routes in advance of the tests, noting how various legs would be tackled. A consistent driving plan was then agreed.

The drivers used voice-activated recorders to record times, distances and litres of fuel consumed as indicated by on-board displays. Fuel consumption was calculated always using the distance measured by the project manager’s car. This provided a consistent figure to use in the mpg calculations and eliminated the risk of error caused by the variations in distance travelled as recorded from one vehicle to another.

Before the road tests began, the vehicles’ engines were tested on a chassis dynamometer to ascertain their precise specification in terms of power (engine and delivered at the wheels) and torque. The results of this testing is discussed in the next section.

4. CHASSIS DYNAMOMETER TESTING

Before conducting any trials of this nature it is important to confirm actual vehicle outputs in terms of torque and power. Older vehicles can lose engine compression, for example, causing their performance to deteriorate. There are many other reasons why vehicles can have more or less horsepower and torque than suggested by the badges on the side of the cab.

All the vehicles in this project were tested on a chassis dynamometer (which is calibrated to an accuracy of ± 1.5% at three separate points) at Feather Diesel Services of Elland, West Yorkshire. The discrepancies found in the vehicles during this project underline the need for such pre-test activity before any tests of this kind.

Badged engine power outputs of the test vehicles and those recorded on the chassis dynamometer are shown in Table 1, in metric horsepower (PS).

Table 1 Actual engine power output of the test vehicles

VEHICLE	BADGED ENGINE HORSE POWER	ACTUAL ENGINE HORSE POWER
2001 Tractive unit 4x2	340	343
2001 Tractive unit 6x2	380	380
2002 Rigid tipper 6x4	310	340
2002 Rigid tipper 8x4	380	396
2004 Tractive unit tipper 6x2	580	591
2006 Rigid tipper 6x2	310	323

In Table 1 and all similar tables the actual engine horsepower is calculated by recording the horsepower delivered at the road wheels and then applying a mathematical formula to estimate the power produced at the engine flywheel. These calculations are performed by the chassis dynamometer equipment.

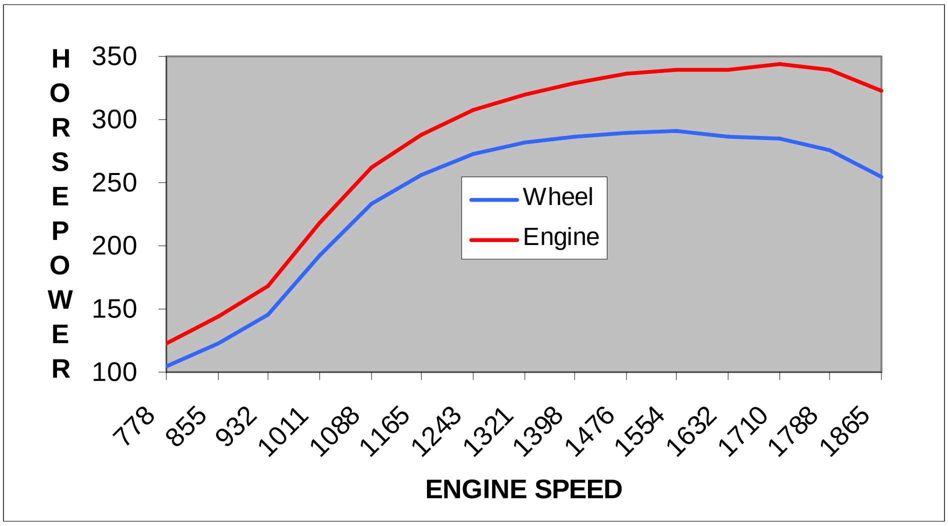
All vehicles in the tipper evaluations were post-02 registrations, whereas the two vehicles in the distribution evaluation were pre-02 registration.

4.1 Tractive unit 340ps 4x2

This is a Volvo FM12 in 4 x 2 configuration, with a 12-litre engine producing 343 horsepower. It can operate at up to 38 tonnes gcw. Many vehicles involved in retail distribution type work rarely operate at the potential maximum gross weight and this vehicle was chosen because it allows great flexibility from an economic viewpoint to operate and in some cases to be taxed in a lower weight band.

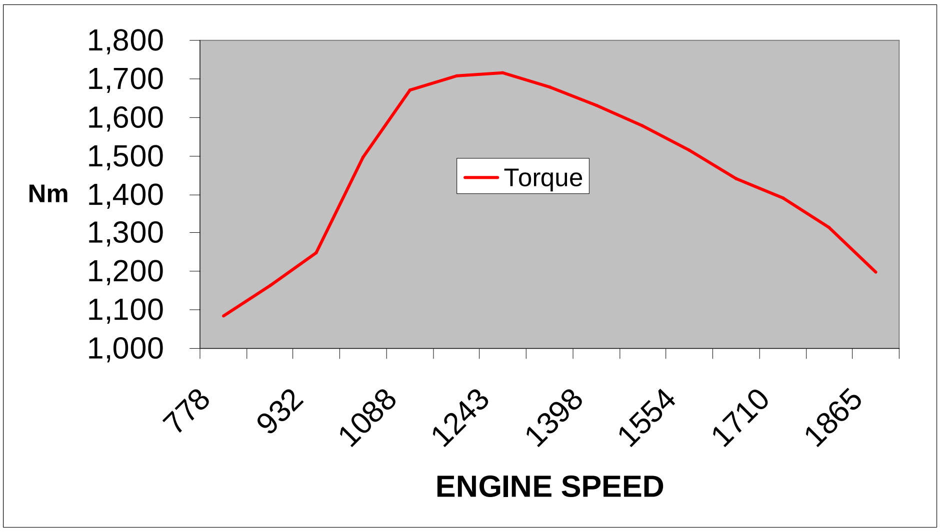
This vehicle had more than 750,000 kilometres on its odometer and the chassis dynamometer showed that the engine was still producing 340 horsepower - the maximum was 343 at 1,710 engine revolutions per minute (rpm). Therefore, the engine was deemed to be suitable for testing. Other 340ps vehicles that had been tested and subsequently rejected were found to be producing engine horsepower that was too high to give a true comparison between a 38 tonne, 4 x 2, 340 and a 44 tonne, 6 x 2, 380 vehicles. Chart 1 below shows the horsepower curves for the engine and delivered by the drive wheels for this particular vehicle.

Chart 1 PS produced by the engine and delivered at the wheel (340)



It can also be seen from Chart 1 that there is a difference between the estimated maximum power at the engine's flywheel and maximum power at the road wheels. In this particular example maximum power at the road wheels occurs at 1,554rpm. Therefore, any engine speed above this wastes energy and provides no benefit to the driver or operator. As can be seen in Chart 2, engine torque peaks at 1,243rpm after which it drops off considerably. It can be seen that the losses due to drag (the vertical differences between the two curves) increases as engine speed rises. This reinforces the message that excessive engine speed not only wastes fuel but does not provide any useful additional power.

Chart 2 Torque produced by the 340 engine



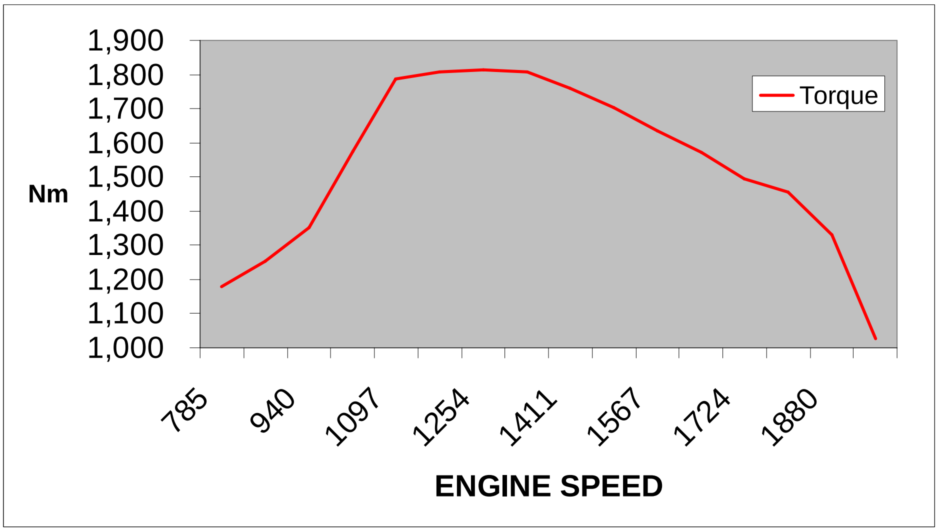
Combining the information from charts 1 and 2 it can be postulated that the most effective driving range is between maximum power at the wheels and maximum engine torque, between 1,243 and 1,554rpm.

4.2 Tractor unit 380ps 6x2

The next vehicle to be checked was a 6 x 2 Volvo FM with 12-litre engine producing 380 horsepower. Pulling a tri-axle semi-trailer, this can operate at up to 44 tonnes gcw. In a modern retail distribution fleets this gives great flexibility, especially when returning to a distribution centre with a load from a supplier when the vehicle can reach its maximum gross weight. As with the 340ps vehicle, there was a difference between maximum engine power and maximum power at the road wheels. This particular vehicle had travelled more than 1,200,000 kilometres and was still producing a maximum of 380 horsepower at 1,802rpm. However, maximum power at the road wheels was achieved at 1,664rpm.

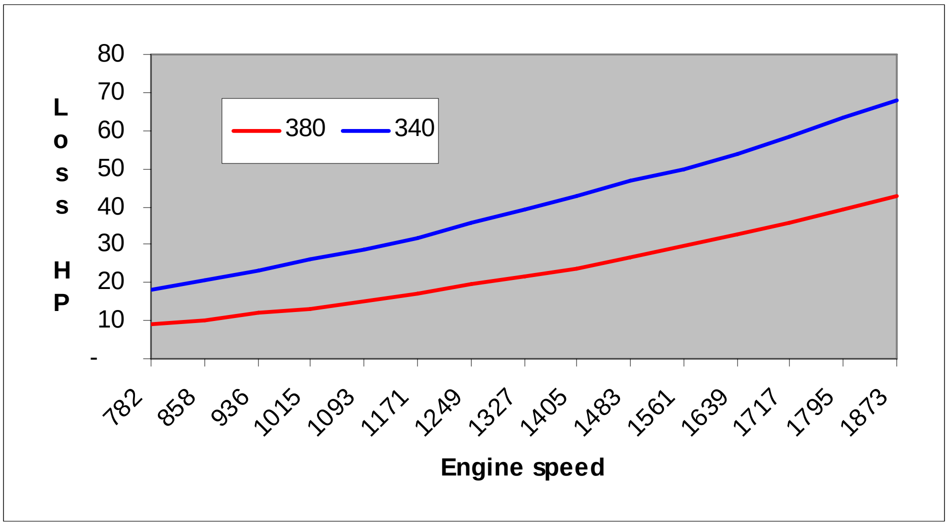
Chart 3 shows the shape of the torque curve which peaks at 1,254 engine revolutions and has a plateau between 1,097 and 1,332rpm.

Chart 3 Torque produced by the 380 engine



Both these tractors had the same gearbox and final drive ratios. So any difference in performance could not be the result of differences in transmission ratios. Differences in drag and rolling resistance identified by dynamometer testing are noteworthy. Chart 4 shows that the 340 horsepower engine uses considerably more horsepower to overcome friction in the transmission system and rolling resistance at the tyres.

Chart 4 Differences in loss of power due to friction and rolling resistance

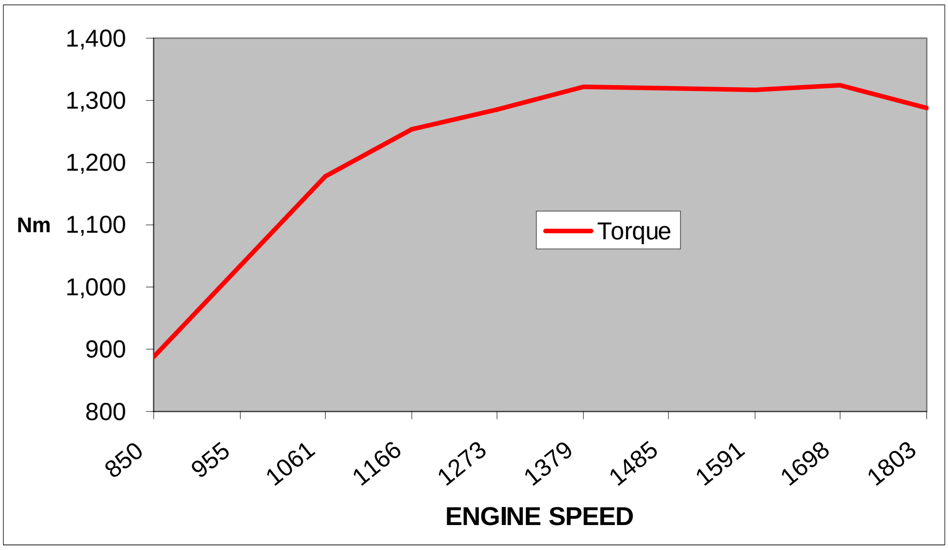


When issues such as this are unearthed they should be investigated to establish the causes and eliminated. In this case eliminating or reducing impact of the causes could enable the 340 vehicle to improve its fuel efficiency. This also suggests that the 340 vehicle might be less fuel efficient than the 380 because more energy is used to overcome friction in the transmission system and rolling resistance.

4.3 6x4 310ps rigid tipper

The 6x4 double-drive tipper was a Daf CF 75 with 9.2-litre engine producing 340ps. This is 30ps more than indicated by the badge on the cab. This type of engine should produce a flat peak torque curve between 1,200 and 1,700rpm. As Chart 5 shows, with this particular engine the almost-flat peak occurs between 1,300 and 1,700rpm.

Chart 5 Torque produced by the 6 x 4 tipper

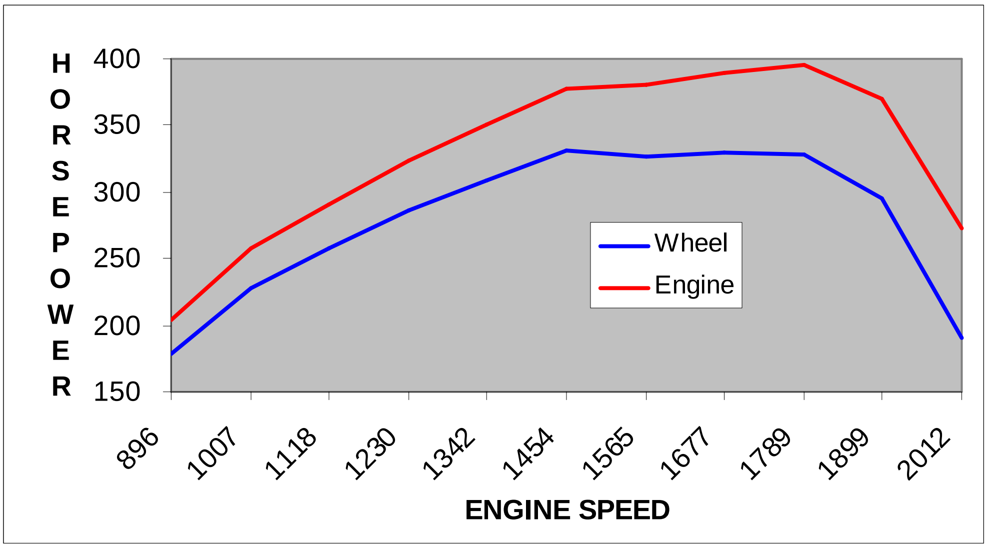


An implication of this is that driving style may need to be adjusted slightly so that engine speed does not drop to the bottom of the green band, at 1,200rpm.

4.4 8x4 380ps rigid tipper

The 8 x 4 rigid was a Volvo FM with a 12-litre engine producing 396 PS. This is 16 PS more than the badged power output. Chart 6 shows that maximum engine power is achieved at 1,789rpm whereas maximum power at the road wheels is achieved at 1,454rpm.

Chart 6 PS produced by the engine and delivered at the wheel 8 x 4 tipper



Increasing engine speed beyond 1,454rpm will produce no discernible operational benefits. The chassis dynamometer indicated that maximum torque was produced at 1,230rpm and that there is a torque plateau between 1,118 and 1,454rpm. There is nothing to be gained by operating the engine outside this speed range.

4.5 6x2 580ps tractor unit with tipping semi-trailer

Though badged as a 580 PS engine, the chassis dynamometer estimated the metric horsepower to be 591 PS. Chart 7 shows that maximum power at the road wheels occurs at 1,763rpm while the engine's maximum power is at 1,959rpm.

Chart 7 PS produced by the engine and delivered at the wheel 560 PS Tipper Unit

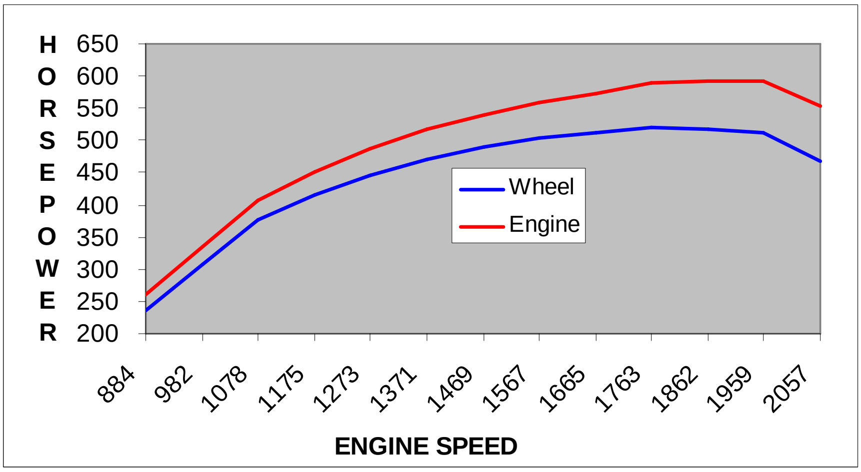
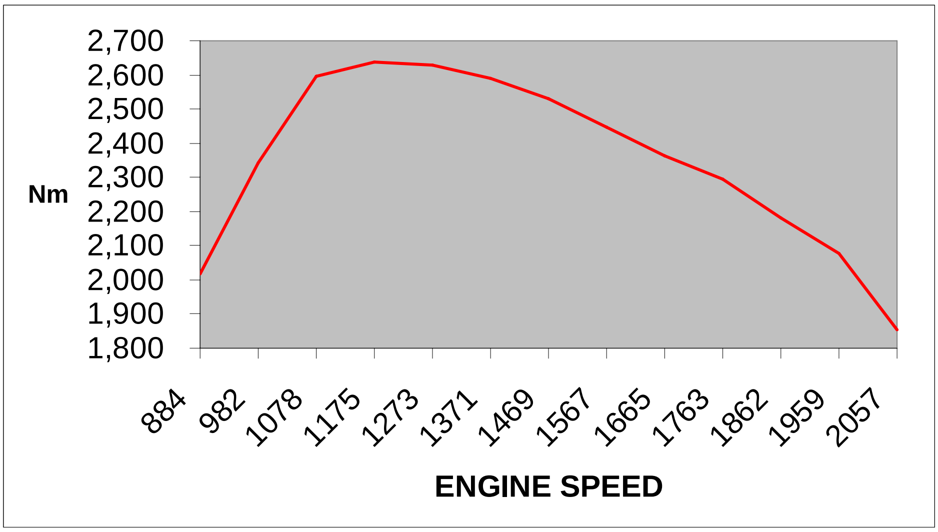


Chart 8 shows that maximum torque occurs at 1,175rpm. Information from these two charts allows a useful engine speed range to be identified.

Chart 8 Torque produced by the 560 PS Tipper Unit



Keeping engine speed between 1,175 and 1,763rpm will ensure that power is not wasted and that maximum torque is available. If engine speed is allowed to drop below 1,078rpm then torque drops off significantly and downshifting through the gears may be required.

4.6 6x2 310ps rigid tipper

The six-wheel tipper appears to be a dying breed in the aggregates industry, possibly because operators want the additional income from operating at a higher gross weight with a bigger payload. But access to non-commercial premises can be difficult or impossible with 8 x 4 rigids. This is why a small number of operators still have three-axle and two-axle tippers. Some are 6 x 2s with lifting third axles. The axle can be raised to improve fuel economy when the vehicle is empty. Access to such a vehicle in this project allowed us to determine the effect on fuel consumption of leaving the third axle down when the vehicle is empty.

5. DISTRIBUTION VEHICLES TEST

Gearbox and final-drive ratios were checked to ensure there was no difference here to affect the test results. Cab gaps and cab roof deflectors were checked to minimise any difference between the two vehicles. Trailers were swapped between tractor units during the test to minimise any bias inherent in an individual trailer. The trailers were loaded using the pallets loaded to the same weight with the same products and in the same position.

Figure 2 Tractor units connected to the test trailers

5.1 DISTRIBUTION VEHICLES TEST ROUTE

The test route consisted of a mix of motorway, dual-carriageway and single-carriageway roads. The datum point for the beginning and ending of the tests was the road beside the entrance and exit to the retailer Somerfield's distribution centre in Bridgwater, Somerset, next to junction 25 on the M5. More detail of the route is in Table 2 below.

Table 2 Sections of the distribution test vehicle route

LEG	DESCRIPTION	ROAD	DISTANCE (MILES)
1	Depot to M5 J27 via J29. All motorway, except for initial depot to J27.	M5	50
2	J27 then A361 towards Barnstable until dual-carriageway becomes single-carriageway.	dual-carriageway	7
3	Continue on A361 towards Barnstable until after 14 miles the turning point is reached. Then back to the dual-carriageway.	single-carriageway	36
4	A361 dual-carriageway to J27	dual-carriageway	7
5	J27 to depot at J25.	M5	22
	Total distance		**122**

This route combines motorway, dual-carriageway and single-carriageway. The fuel economy on separate legs of the journey can be determined to identify any sensitivities that any vehicle might have to the route. Table 3 contains the data obtained during the first run when the vehicle travelled solo or bobtail. This illustrates how overall mpg can be influenced by length of individual legs.

Table 3 First run – solo

Leg	mpg from 340ps 7,020 kg	mpg from 380ps 8,180 kg
1	10.52	10.77
2	15.91	15.15
3	17.60	16.70
4	15.91	14.46
5	14.29	14.29
Overall	13.24	13.41
Time taken (minutes)	150	150

The 340 vehicle equalled or outperformed the 380 on all but the first leg. However, because the first leg comprises 41 per cent of the test route, the 380ps tractor is the more fuel efficient at this stage of the evaluation process. Both vehicles covered the distance in the same time. But the distance travelled solo by a tractor is unlikely to be significant during its working life.

The results of the first test with the trailer pulled by the tractor are shown in Table 4. A dramatic change in fuel consumption is due not only to the increased weight but also to changed aerodynamic properties. This means that two variables (weight and aerodynamic resistance) have been altered. Therefore the first data set that can be used in terms of evaluating the impact of increasing payload comes from comparing Tables 4 and 5.

Table 4 Second run – both empty

Leg	mpg from 340 at 15,600kg	mpg from 380 at 16,500kg
1	9.32	9.55
2	12.73	11.79
3	11.95	11.44
4	11.79	10.97
5	11.91	12.05
Overall	10.75	10.67
Time taken (minutes)	148	150

Examination of the data produced by the two vehicles indicates that the 340 still has the advantage on single- and dual-carriageways whereas the 380 maintains an advantage (albeit reducing) on motorway sections. Overall the 340 has the better mpg by a margin of 0.8mpg (0.75%) which could be within the range of experimental error due to rounding.

When comparing the data in Tables 4 to 9 it is important to look at performance by leg as well as overall performance. This will enable development of matrix-style planning in that operators can compare the distance and expected fuel consumption for operating on different categories of road at different weights and thereby develop their own optimum solution.

This was the first run where the vehicles carried a payload. Both operated at 18 tonnes gcw. It can be seen in Table 5 that the 380 has nudged in front of the 340 by 0.02mpg (0.19%) a very small margin and again possibly within the range of experimental error.

Table 5 Third run – 18 tonnes gcw

Leg	Mpg from 340ps	mpg from 380ps
1	8.98	9.13
2	12.73	11.79
3	11.13	10.91
4	11.79	11.37
5	12.05	12.66
Overall	10.48	10.50
Time taken (minutes)	150	150

Again the 340 outperforms the 380 on the single- and dual-carriageway sections whereas the 380 wins on motorway sections with no difference in time recorded. Increasing the payload by the first of the five-tonne increments produced the data in Table 6. Two points need to be noted with reference to these data. The first is that when this run was undertaken the wind speed and temperature were both much more favourable than they were for the previous and following runs. Second, the mpg of 14.46 is very high and could be due to the reading being taken just before the display changed.

Table 6 Fourth run – 23 tonnes gcw

Leg	mpg from 340ps	mpg from 380ps
1	9.39	9.47
2	14.46	10.97
3	9.41	9.41
4	10.27	8.84
5	11.50	11.77
Overall	9.98	9.83
Time taken (minutes)	156	153

A time difference of three minutes is recorded, and the overall difference in fuel consumption is now 0.15mpg (1.5%) in favour of the 340, which maintains its lead in non-motorway sections though the 380 still outperforms the 340 on motorway sections. As payloads increase this situation begins to change, see Table 7.

Table 7 Fifth run – 28 tonnes gcw

Leg	mpg from 340ps	mpg from 380ps
1	8.61	8.33
2	10.61	9.94
3	8.27	7.91
4	8.84	8.37
5	10.64	10.42
Overall	8.92	8.59
Time taken (minutes)	156	160

The 340 now outperforms the 380 in all five legs by more than 0.2mpg and overall by 0.33mpg. This could have a significant impact on fuel costs for an operator. But the time difference has now extended to four minutes in favour of the 380. The weight was again increased by five tonnes and the performance data is shown in Table 8.

Table 8 Sixth run – 33 tonnes gcw

Leg	mpg from 340ps	mpg from 380ps
1	8.12	7.98
2	10.27	9.94
3	7.41	7.34
4	8.60	7.58
5	10.10	10.21
Overall	8.3	8.16
Time taken (minutes)	160	165

The difference in time has now extended to five minutes in favour of the 380 though in terms of fuel consumption the 340 continues to outperform the 380, albeit by a smaller margin of 0.14mpg (1.72%). However, there is a consistency to the data which will be discussed at the end of this section. The final five-tonne increment took the 340 vehicle to its maximum gross weight of 38 tonnes. The data produced are shown in Table 9.

Table 9 Seventh run – 38 tonnes gcw

Leg	mpg from 340ps	mpg from 380ps
1	7.87	7.60
2	9.36	9.09
3	6.73	6.42
4	7.96	7.07
5	9.44	9.35
Overall	7.79	7.48
Time taken (minutes)	163	160

It can be seen that the 340 maintained its position as the most frugal vehicle, in this particular run by 0.31mpg (4.14%) and it was the most fuel efficient in all legs. This shows clearly that increasing horsepower does not necessarily result in greater fuel efficiency at heavier weights. The time difference has also reduced to three minutes. A final run was done with the 380 vehicle loaded to its maximum gross weight of 44 tonnes and the results are shown in Table 10.

Table 10 Eighth run– 44 tonnes gcw

Leg	mpg from 380ps
1	7.06
2	7.76
3	5.70
4	6.24
5	8.93
Overall	6.82
Time taken (minutes)	173

The addition of six tonnes of payload resulted in an overall drop in mpg of 0.66. The driver of the 340ps vehicle accompanied the driver of the 380ps vehicle on this last run to ensure there was no difference in driving style.

5.2 COMPARISON OF THE 340 AND 380PS VEHICLES

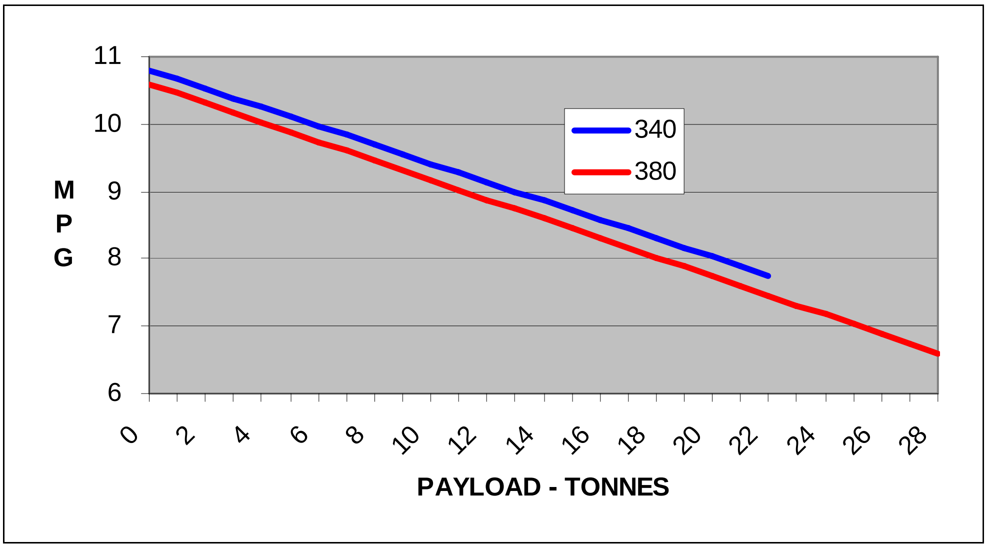
The 340 was more frugal on the single- and dual-carriageway sections than the 380. In the initial stages with lighter payloads the 380 outperformed the 340 on motorway sections but as weight increased the 340 became the more fuel efficient vehicle on all sections. The difference in fuel consumption in the normal working range of empty to 33 tonnes fluctuated between 0% and 4% in favour of the 340. Though the sample size in this project is small, the difference in fuel consumption is reinforced by previous research carried out by Somerfield, using live data collected over several weeks. Analysis of that data conducted several years ago showed 340ps tractors to be 3% more fuel-efficient than 380ps tractors.

5.3 ANALYSIS OF THE DATA

One outcome of the research is payload-against-fuel-consumption curves based upon the data. A linear regression model was found to have an exceptionally high standard of fit for both the 340ps and 380ps vehicles. Output from this analysis is in Appendix A.

The formula for the 340ps truck contains a constant or intercept of 10.8mpg, and fuel use increases by 0.139mpg for every tonne of payload added to the vehicle. The formula for the 380 is a constant or intercept of 10.6mpg, and fuel use increases by 0.143mpg for every tonne of payload added. Chart 9 shows the differences between the two. This will be discussed further in Section 7.1.

Chart 9 Regression lines of the distribution vehicles



It can be seen that both vehicles start with more or less the same fuel consumption when empty (though the 380 is almost one tonne heavier). As payload is increased the vehicle with the 340ps engine increases the difference in fuel efficiency compared with the vehicle with the 380ps engine.

The difference in time taken to travel the route never exceeded five minutes. It is possible that the time difference in a daytime test would have been even less, owing to the influence of traffic.

6. TIPPER VEHICLES TEST

This trial consisted of operating vehicles of three different configurations and gvw, so a comparison of the effects of engine sizes could not be undertaken. A route was planned to be representative of a typical tipper operation and is discussed below.

6.1 TIPPER VEHICLES TEST ROUTE

Vehicles engaged in aggregates industry tipper work tend to operate locally, making several deliveries per day. This involves returning empty to their quarry or plant to collect a fresh load for delivery. Typically, routes consist of a mix of single-carriageway, dual-carriageway, urban and rural driving. The test route was designed to represent a local operation and includes a large proportion of single-carriageway and a small proportion of dual-carriageway as well as a small amount of town driving to represent delivery to a building site. Details of the route are in Table 11.

Table 11 Sections of the tipper vehicle test route

LEG	DESCRIPTION	DISTANCE (MILES)
1	URBAN	2.0
2	SINGLE-CARRIAGEWAY	3.9
3	DUAL-CARRIAGEWAY	1.8
4	SINGLE CARRIAGEWAY INCLUDING TURNING POINT	12.6
5	DUAL CARRIAGEWAY	1.8
6	SINGLE CARRIAGEWAY	3.9
7	URBAN	2.0
	TOTAL DISTANCE	**28**

Note: the turning point is that part on the route (a roundabout) where the vehicle does a 180 degree turn and then retraces its route. This enabled data to be collected in both directions.

The overall fuel consumption figures for the tests with the tipper vehicles are set out in Tables 12 to 14, showing vehicle operating weight and fuel consumption in mpg as well as litres per tonne per kilometre, as introduced by McKinnon (BG 78, 2003).

6.2 6x4 AT 26 TONNES GVW

This vehicle is a Daf 310ps three-axle, double-drive 26 tonnes-gvw rigid, shown in Figure 3.

Figure 3 6 x 4 test vehicle

The vehicle travelled the route empty to establish an initial mpg figure, after which it was loaded with a 6.74-tonnes payload - one third of the payload of the 32-tonnes-gvw vehicle. The vehicle was then loaded to its maximum gvw.

Table 12: 26 tonne 6x4 fuel consumption

CONDITION	MPG	L/T/KM	Time (mins)
Empty – 9.580 tonnes	14.14	0.021	53
16.320 tonnes gross	9.79	0.018	56
26 tonnes gross	7.96	0.014	61

The figures in Table 12 show that running empty on this route the average fuel consumption was 14.14mpg. Fully loaded, the vehicle's mpg fell to 7.96. However, the l/t/km has improved dramatically, as might be expected. The impact on journey time caused by increasing the vehicle's weight is quite noticeable.

With only three reference points, great care must be taken when interpreting the regression model. As shown in appendix A, the examination revealed that the coefficient for the payload had a P value of 0.212, which would normally exclude its use because generally a P value equal to or below 0.05 would be necessary for the inclusion of the variable – in this case the payload. However, it has been applied in this case to give an indication as to the effect of increasing the payload rather than to state an absolute effect.

Additionally, because no applicable model could be found from previous research it serves to advise other researchers of the need to conduct more test runs.

6.3 8x4 at 32 tonnes gvw

This vehicle is a 380ps Volvo four-axle, double-drive 32-tonnes-gvw rigid tipper, as shown in Figure 4.

Figure 4 8 x 4 test vehicle

The 32-tonnes-gvw vehicle ran empty for its first run and then its weight was incrementally increased by a third of its payload - three times. The impact upon fuel consumption in terms of mpg and l/t/km can be seen in Table 13.

Table 13: 32-tonnes 8x4 fuel consumption

CONDITION	MPG	L/T/KM	Time (mins)
Empty - 11.760 tonne gross	12.24	0.020	49
18.493 tonne gross	9.29	0.016	55
25.227 tonne gross	7.49	0.015	56
32 tonne gross	6.40	0.014	57

The figures in Table 13 show that when running empty on this route the average fuel consumption was 12.24mpg. Fully loaded, the vehicle's mpg fell to 6.4. But the l/t/km has improved, as might be expected. The impact on journey time of the increasing weight of the vehicle is interesting in that once the first load is added there is a substantial increase but after this point the impact is less.

6.4 Three-plus-three at 44 tonnes gcw

This vehicle is a 580ps Scania three-axle, 6x2, 44-tonnes-gcw tractor (shown in Figure 5) coupled to a three-axle tipping semi-trailer.

Figure 5 Tractor unit and trailer for the tipper test

The 44-tonnes-gcw tractor and trailer was empty for its first run and then its weight was increased to 26 tonnes gross followed by 32 tonnes gross and finally 44 tonnes gross. Both the mid-lift axle on the tractor and the front lift axle on the trailer were raised to increase fuel efficiency when the weights were low enough to do so. The impact upon fuel consumption in terms of mpg and l/t/km is clearly indicated in Table 14. It also allows comparison with the other two vehicles when running empty and at their maximum weight.

Table 14: 44 tonnes 3 + 3 fuel consumption

CONDITION	MPG	L/T/KM	Time (mins)
Empty – 15.760 tonnes gross	10.27	0.017	55
26 tonne gross	7.44	0.015	57
32 tonne gross	6.53	0.014	58
44 tonne gross	5.51	0.012	57

Note: all but the last run were completed with the mid lift axle raised.

This is the heaviest of the three vehicles and has to transport more dead weight than the others. It also has the largest engine. Comparison of the l/t/km figures for the three vehicles shows that the 44 tonne vehicle is the most efficient when operating at its maximum gross weight. The vehicle took longer to complete the route when empty but the increase in weight had a small effect upon journey time. The conclusion to be drawn from this is that the vehicle's size probably slowed it down in the urban sections and that its engine power and torque along with the driver's skill was able to minimise the effect of the increase in weight.

During the research programme an opportunity arose to test a 6x2 tipper. The data from this test are shown in Table 15.

6.5 6x2 at 26 tonnes gvw

This vehicle's lifting third axle enabled an assessment to be made of the impact on fuel consumption of raising the third axle when the vehicle is empty. The vehicle's unladen weight is 9.340 tonnes.

Table 15: 26 tonne 6x2 fuel consumption

CONDITION	MPG	L/T/KM	Time (mins)
Empty - axle up	15.52	0.019	59
Empty - axle down	14.80	0.020	55

It can be seen in Table 15 that when the vehicle is empty and the dead axle lowered it has a negative effect upon fuel consumption of the order of 0.72mpg. This figure should be interpreted as indicative because it was based upon one run under each condition and more in-depth statistical analysis could not be applied.

7. IMPACT OF PAYLOAD ON MPG

Increasing a vehicle's weight will increase its fuel consumption. This section examines this relationship in the two types of operation observed in the research. Linear regression was used to determine the intercept and slope of the relationship.

7.1 DISTRIBUTION

Using the data collected it was possible to establish whether there is any specific relationship between fuel consumption and vehicle weight. A previous test conducted by the British Transport Advisory Committee (BTAC) in 2000 at the Motor Industry Research Association (Mira) proving ground found an average deterioration of 0.144mpg for every one tonne increase in weight. That test on the Mira track was conducted using a similar Somerfield Volvo FM12, 4x2 tractor unit and trailer and it enables verification of the results with the on-road testing that took place as part of this research. The results from this on-road test are summarised in Table 16.

Table 16: Impact per tonne – tractor unit and semi-trailer

RUN	340ps MPG	WEIGHT INCREASE TONNES	IMPACT PER TONNE ON MPG	380ps MPG	WEIGHT INCREASE TONNES	IMPACT PER TONNE ON MPG
1	13.24			13.41		
2(1)	10.75	8.42	0.296	10.67	8.42	0.294
3	10.48	2.56	0.103	10.50	1.40	0.115
4	9.98	5.00	0.102	9.83	5.00	0.134
5(2)	8.92	5.00	0.212	8.59	5.00	0.250
6	8.30	5.00	0.123	8.16	5.00	0.086
7	7.79	5.00	0.103	7.48	5.00	0.134
8				6.82	6.00	0.110

(1) The change in fuel consumption is also due to an increase in aerodynamic resistance, because the trailers have been attached.

(2) The weather deteriorated during this run: wind speed increased and it became colder.

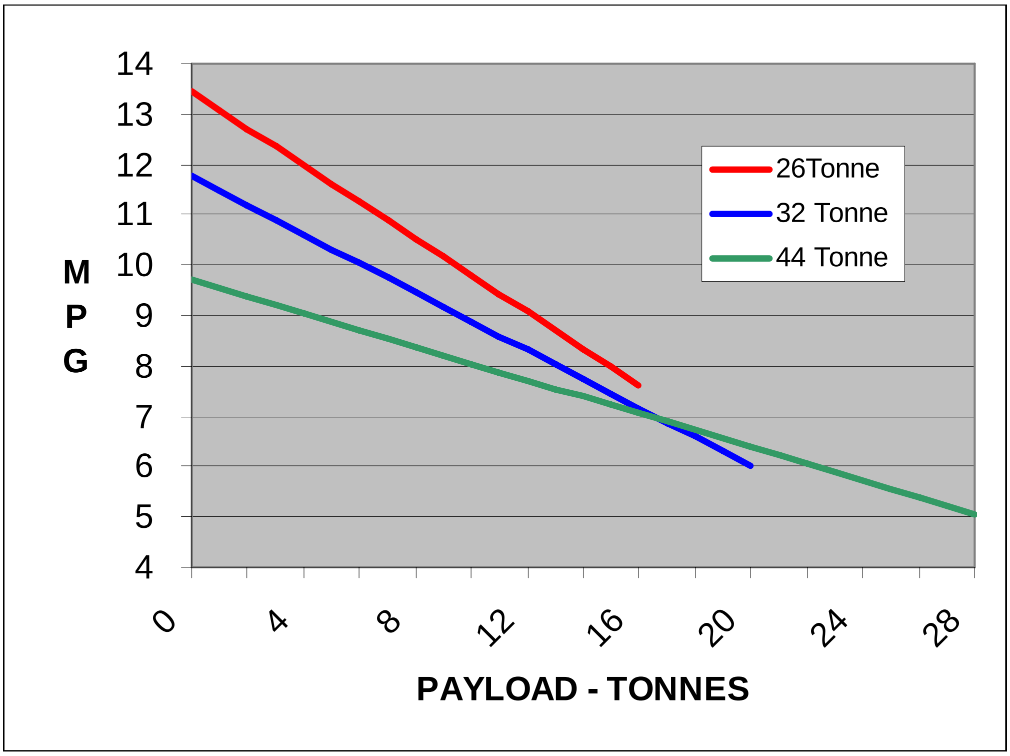
With such a small sample great care must be exercised. This is why the data are examined both with and without data associated with these two runs. Statistical analysis suggests that run 2 should be classified as an outlier and run five a straggler.

Using data from the two vehicles it has been established that the average impact on mpg per tonne of increased payload is 0.112 with a standard deviation of 0.016. This is very close to the 0.144 figure established by BTAC in 2000, the difference being 0.032. Therefore, the 0.112 figure should be considered to be robust and reliable.

7.2 Impact of payload on mpg - tippers

Linear regression was used to determine the impact upon fuel consumption of increasing the payload – a summary of the input is contained in Appendix A. The slopes shown in Chart 10 are based upon the regression equations that were produced and though the “goodness of fit” measures are strong it is clear from the analysis of the figures in Appendix A that the equations that produce the lines in chart 10 should be seen as indicative rather than conclusive. This is primarily due to the fact that the vehicles did fewer runs than the distribution vehicles.

Chart 10 Regression lines of the tipper vehicles



It can be seen in Chart 10 that the 44-tonne vehicle has a better fuel consumption than the 32-tonner when the payload exceeds seventeen tonnes. This illustrates the opportunity for an operator of a 44-tonne vehicle who is asked to deliver loads that would be allocated to a 32-tonner to maximise income and minimise fuel costs. If the capped load rate is paid, the 44-tonne operator will increase profitability even more.

8. CONCLUSIONS

One of the most important findings of this project is the importance of checking vehicle horsepower and torque on a chassis dynamometer before beginning any actual testing. Without such checks, tests may be of vehicles with almost identical horsepower and torque though badged as different. Without such checks, a test programme could be invalid.

The chassis dynamometer test is also useful for identifying energy losses in the drivetrain and due to rolling resistance. If necessary, measures can be introduced to minimise these losses before tests begin.

The distribution vehicle tests show that higher horsepower engines do not necessarily deliver greater fuel efficiency or save much time. Over the life of a vehicle it is quite likely that fuel costs will be the largest overall cost and any difference in residual values between different vehicles might not compensate for the difference in total fuel costs. This also underlines the need for operators to conduct whole-life cost appraisals.

The correct specification of a vehicle is paramount if fuel consumption is to be minimised. From the point of view of fuel efficiency it is the correct matching of engine output, namely engine torque, and gearing ratios that are important.

A lot of fuel is used to move a vehicle when it is empty. Therefore any techniques or technologies or materials that can reduce this dead weight without increasing other costs may be of significance, not only because payload will increase (and thus income) but also because less fuel will be consumed when running light or empty. This is of particular importance to operators of tipper vehicles which sometimes spend up to 50% of their time empty.

The research underlines that higher-power engines do not necessarily result in better fuel economy and though a higher-power engine could have a greater residual value this might not be financially advantageous when increased fuel use is taken into account.

9. RECOMMENDATIONS

1. All vehicles to be used in such tests should undergo checks on a chassis dynamometer so that their true performance characteristics are known and recorded. Additionally, any losses within the drivetrain and due to rolling resistance can be quantified.

2. Driver influence on the vehicle performance should be minimised. In this project SAFED instructors were used as drivers, to reduce the driver variable and their influence on fuel consumption.

3. Due to the impact of rounding on fuel consumption figures, longer legs in test runs should be considered. Though this will increase time and cost it will produce more robust data which should have a greater degree of accuracy.

4. Operators need to be aware that more horsepower does not necessarily mean lower fuel bills. It is about correct specification - getting the powertrain correct. Most vehicle manufacturers have computer modelling programs enabling different specifications of vehicle (power, torque and transmission ratios) to be compared and performance figures produced.

5. Whenever economically possible, a vehicle's weight should be minimised to reduce fuel costs when running empty or light and to maximise payload. This is something that can involve both vehicle manufacturer and body builder.

6. Those operators who operate equipment with lifting axles should ensure that drivers know how to use the equipment correctly and that it is properly maintained to minimise fuel costs.

7. The charts produced in this report could be used as part of an operator and driver education programme to show that maximum engine power does not equate to maximum power at the drive tyres and that help should be sought from the vehicle manufacturer to identify the optimum engine speed range rather than just relying on the green band.

8. Most modern vehicles are fitted with an on-board computer (OBC) and on-board display (OBD) and these should be used to develop performance characteristics for vehicles as in tables 3 – 10 and 12 – 15. This information can then be used to optimise the allocation of the present fleet and the specification of future vehicles.

9. Further research should be conducted to determine whether engines with higher than expected power outputs are common.

10. The research should be continued to determine the causes of the increased power losses as indicated by the dynamometer tests on the 340ps and 380ps vehicles used in the distribution vehicles test.

10. APPENDIX A – REGRESSION ANALYSIS

Results of regression analysis for 340 PS distribution vehicle.

Regression Statistics	
Multiple R	0.99
R Square	0.99
Adjusted R Square	0.99
Standard Error	0.15
Observations	6

ANOVA

	df	SS	MS	F	Significance F
Regression	1	7.26	7.26	335.57	0.00005
Residual	4	0.09	0.02		
Total	5	7.35			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.80	0.10	109.56	0.00000	10.53	11.08
Payload	0.139	0.01	18.32	0.00005	-0.16	0.12

Results of regression analysis for 380 PS distribution vehicle.

Regression Statistics	
Multiple R	0.992
R Square	0.985
Adjusted R Square	0.982
Standard Error	0.199
Observations	7

ANOVA

	df	SS	MS	F	Significance F
Regression	1	13.02	13.02	329.32	0.00001
Residual	5	0.20	0.04		
Total	6	13.21			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.60	0.12	86.78	0.00000	10.28	10.91
Payload	0.143	0.01	18.15	0.00001	0.16	0.12

Results of regression analysis for 26 Tonne 310 (340) PS 6 x 4 tipper vehicle

```
SUMMARY OUTPUT

Regression Statistics
Multiple R                 0.945
R Square                   0.893
Adjusted R Square          0.786
Standard Error             1.472
Observations               3

ANOVA
                  df       SS                MS                F        Significance F
Regression        1        18.03             18.03             8.33     0.212
Residual          1        2.17              2.17
Total             2        20.20

                  Coefficients      Standard Error  t Stat   P-value           Lower 95%         Upper 95%
Intercept         13.44             1.29            10.40    0.061             -2.98             29.85
Payload           0.364             0.126           -2.89    0.212             -1.966            1.238
```

Results of regression analysis for 32 Tonne 380 PS 8 x 4 tipper vehicle

```
Regression Statistics
Multiple R                 0.977
R Square                   0.955
Adjusted R Square          0.933
Standard Error             0.660
Observations               4

ANOVA
                  df       SS                MS                F                 Significance F
Regression        1        18.687            18.687            42.887            0.023
Residual          2        0.871             0.436
Total             3        19.559

                  Coefficients      Standard Error  t Stat   P-value           Lower 95%         Upper 95%
Intercept         11.754            0.552           21.28    0.002             9.38              14.13
Payload           0.287             0.044           6.55     0.023             0.475             0.098
```

Results of regression analysis for 44 Tonne 580 PS 6 x 2 Tractor Unit

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.955
R Square	0.912
Adjusted R Square	0.868
Standard Error	0.743
Observations	4

ANOVA

	df	SS	MS	F	Significance F
Regression	1	11.434	11.434	20.715	0.045
Residual	2	1.104	0.552		
Total	3	12.538			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	9.701	0.621	15.63	0.004	7.030	12.37
Payload	0.165	0.036	4.55	0.045	0.322	0.009

11. PROJECT PARTICIPANTS

The project succeeded due to the hard work of the project participants who are listed below with full apologies to anyone who has been missed off the list.

Lead Contractor
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Alan Calder
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Ian Greedy
Stuart Allen
David Chidley
Steven Smith
Rob Webb
Mark Redfern

12. ABBREVIATIONS & GLOSSARY

Table 17 Abbreviations

ABBREVIATION	FULL TITLE
MPG	Miles per gallon
GCW	Gross combination weight
GVW	Gross vehicle weight
l/100 km	Litres of fuel consumed per 100 kilometres travelled.
SAFED	Safe and Fuel Efficient Driving
PS	Metric Horsepower
RPM	Revolutions per minute
L/T/KM	Litres per tonne per kilometre

Table 18 Glossary

ITEM	EXPLANATION
4 x2	A vehicle with four wheel assemblies of which two are driven.
6 x 2	A vehicle with six wheel assemblies of which two are driven.
6 x 4	A vehicle with six wheel assemblies of which four are driven.
8 x 4	A vehicle with eight wheel assemblies of which four are driven.
3 + 3	A three axle tractor unit attached to a tri-axle trailer.
Chassis dynamometer	A machine for establishing the power and torque delivered to the driven road wheels.
Metric Horsepower	The power which raises 75 kilograms against the force gravity through a distance of 1 metre per second.
P Value	The probability of a statistic (assuming that a null hypothesis is true) of obtaining a value at least as extreme as the one obtained. Traditionally, the null hypothesis is accepted if the value us greater than 0.05.
Double Drive	Both rear axles are driven.
Drivetrain	From the input shaft of the gearbox to the end of the half-shaft or hub reduction gears if fitted.