

**METHODS TO CALCULATE AND DECLARE
FUEL CONSUMPTION FOR HEAVY NON ROAD
MOBILE MACHINERY PART II**

LITERATURE AND SIMULATION STUDY

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ABSTRACT

A second and deeper investigation of methods for fuel consumption measurement on non road mobile machinery have been performed. In this investigation mainly two activities have been conducted; interviews regarding tractor fuel consumption measurement methods and simulations regarding fuel consumption for wheel loaders. In the case of methodology for fuel consumption measurements for tractors, the German Agricultural Society approach is considered to be the best method available and has to some extent become an unofficial industrial standard for testing tractor fuel consumption. There is however a caveat: no conclusions can be drawn yet as to how much variations in ambient conditions effect the results. This issue must be clarified before the methodology can be considered for certification purposes.

The simulation study of a wheel loader shows that total cycle distance and vehicle acceleration/deceleration has the highest impact on the cycle fuel consumption. Sand pit resistance, or how hard the driver pushes into the pit also have an impact on the cycle fuel consumption. The efficiency of the hydraulics, the rolling resistance of the wheel loader and how high the bucket load has to be lifted have low impact on the cycle fuel consumption. Using a constant bucket load vs. actually loading and dumping the load has a low impact on fuel consumption suggesting that, if necessary, a fixed bucket load may be used (as described in the JCMAS H022 method).



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1 INTRODUCTION

1.1 Project definition

The project is funded by the Swedish Road Administration. The machines included in the scope of this second report are tractors and wheel loaders.

The project consists primarily of:

- Gather additional and supplementary information regarding fuel consumption testing for tractors
- Simulate a driving cycle for a wheel loader and evaluate the impact of variations in the setup of the cycle

1.2 Background

As this report follows up on previous investigations of the test methods for non-road mobile machinery, NRMM, a more extensive and thorough background chapter can be found in the previous report [1]. In short, the total fuel consumption in Sweden for the NRMM is approximately half of that used in the land-based transport sector. Previously the fuel consumption for NRMM have not had the same attention as that of the transport sector, however as both legislative and voluntary CO₂ criterions are being put into effect it is clear that suitable methodologies and test cycles are a necessity for this segment also.

2 INFORMATION COLLECTED

2.1 Tractors

2.1.1 *The German Agricultural Society, DLG*

DLG is the German Agricultural Society which perform agricultural machinery tests at their test centre located near Groß-Umstadt in mid Germany. The test facilities employ around 50 people and include a test track for the specific task of tractor testing. In addition to the tractor testing expertise DLG also perform extensive testing relating to farming and farming implements. DLG has one PTO dyno as well as 3 dynos for engine testing located in Groß-Umstadt. The PTO dyno is used to both perform the OECD test protocol as well as to determine the appropriate load factor for the PowerMix cycles. The fuel measurements with the PTO dyno are performed using fuel balance scales and fuel conditioning devices. The measurement accuracy is well below the requirement stated in the OECD standard, which is 1%.

The testing equipment for the PowerMix cycles and the definition of the actual cycles are all described in [1], a short description is however also included here. The test method is based on outdoor testing on test track and on roads using a

truck with braking (drawbar power), a shaft connection (PTO power) and a hydraulic valve system (hydraulic power) to vary the load on the tractor. See Figure 1 and Figure 2.



Figure 1, Tractor pulling the DLG load car on the test track

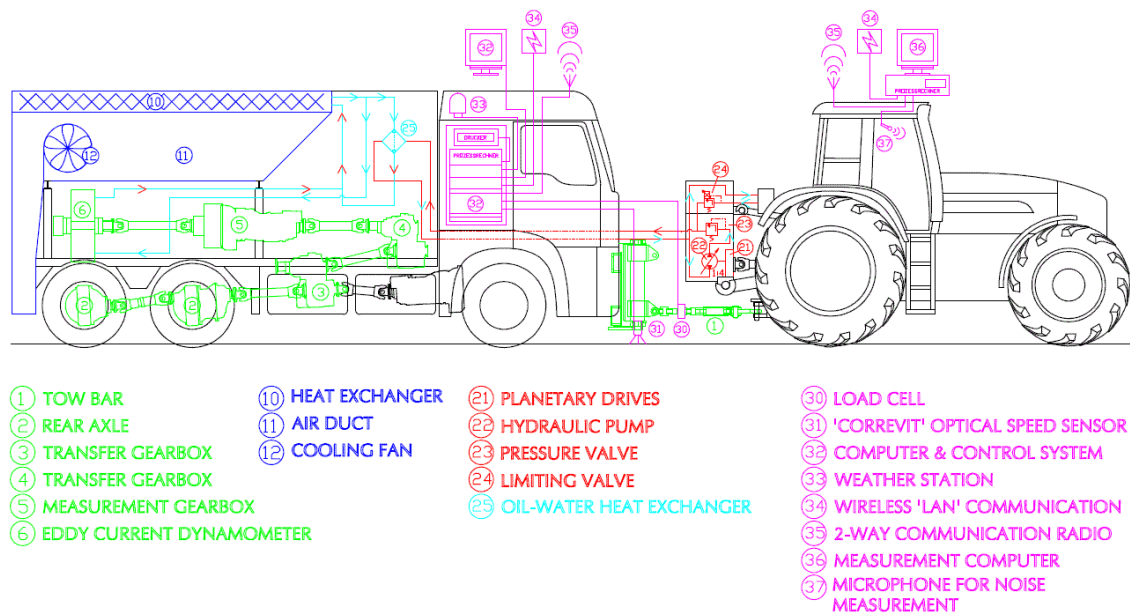


Figure 2, DLG load car instrumentation and system layout

Since power output from the tractor can be extracted in three different ways, independently and if necessary simultaneously of one another, the applied cycles can be freely designed, based on on-board measurements. The fuel consumption cannot be measured in the dyno car using fuel balance scale due to the movement of the vehicle. Instead a PLU system from Pierburg is used.

The DLG test track is 440 meters long, made out of concrete slabs and is oval in shape. The PowerMix test is performed using the complete track, including the two 180° curves. The friction coefficient of the track is extremely good, values above 1,0 are frequently attained. The concrete slabs have been levelled using a diamond tipped grinder after proper seating in the ground. This ensures that there are no height differences between the slabs at the joints.

The tests performed at the track can only be performed during dry conditions. An ideal track would consist of a 1500 meter straight concrete track under cover but this is too expensive.

A defined circuit on public roads in the nearby area is included in the test procedure for fuel consumption testing during fast transport work.

The loads on the tractor are derived from the measurement at the pto. The maximum measured power is used for calculating the power requirement from the tractor. If the tractor engine has boost power, the maximum power with boost is used for scaling those cycles where boost is activated, depending on driving speed and/or use of the PTO. Wheel slip lies in the range of up to a



maximum of 10%, as the loads in the drawbar cycles are not so high as to get near maximum drawbar force, which depends on the tractor's weight.

In the procedure of preparing a test, the fuel consumption data from the full load test with the PTO dyno is compared to the same full load operating point using the dyno car. The resulting full load fuel consumption measured with the dyno car must not deviate more than 1% from the measured fuel consumption from the PTO test.

The addition of the apparatus controlling PTO load results in a 950 kg load applied at the 3-point hitch system typically at the back of the tractor (front mounting is however also possible). This load must be balanced with additional ballast on the other end of the tractor so that a 40-60% weight distribution is achieved. Hydraulic oil cooling is allowed in the dyno car, but is normally done using the tractor oil cooling system. It is possible to also perform a zero load test in order to measure the parasitic losses of the tractor only. This is accomplished using pumps (to counteract the hydraulic losses for the PTO driveshaft) and by driving the dyno car behind (so that no load is applied at the drawbar). DLG is extending their road load tests with the addition of a trailer for lighter draw bar loading. The use of the dyno car on public roads is however not recommended due to safety concerns as the braking behaviour of the dyno car is not similar to that of a trailer and the weight of the dyno car of 27 t cannot be reduced (e.g. for tractors with low power).

The main beneficiary of the test data is the farmer according to DLG. The experience of DLG is that the use of specific fuel consumption in g/kWh is highly relevant as a measure of the effectiveness of the tractor and that the PTO tests and the PowerMix tests often show a correlation of good or bad fuel consumption. There have been many discussions for translating the virtual implement of the PowerMix (since it is perfectly adapted to the power of the tractor) to a fuel effectiveness described in kg/hectare for example. This interpretation or recalculation of the results are of course possible. However, it is not the recommendation of the DLG to optimize or change the cycle for each tractor to increase fuel effectiveness since there are several factors that come into place when correlating the work load of the tractor to time. Most significantly the influence of the driver. For example, the distance travelled varies to a large degree based on the speed. The distance travelled does not have the same requirements as for some implements in which a desired speed must be maintained for a satisfactory quality output. Instead the speed is simply based on the drivers sensitivity to time versus fuel consumption. In addition it is the experience from DLG that the kg/hectare measured values are similar for most sizes of tractors which again does not help the farmer with his selection of tractor as it is also a matter of consideration of how much time the farmer finds acceptable for a certain type of work. Again, this time can be effected by the



farmer in the selection of speed and thereby the weighing of fuel consumption and working time costs respectively. An approximated fuel consumption difference between a hurried work and the ideal PowerMix test can according to the DLG be as large as 10-15%.

The driver influence of the test results are of course minimized as far as possible, but it cannot be avoided completely with the selection and change of gears for example on tractors with a stepped gear box. From the PTO tests and the knowledge of gear ratios the selection of gears can however be planned beforehand in order to minimize this effect. Tractors with CVT gear boxes and engine/gearbox management show the advantages of these features very clearly in the test.

The PowerMix test protocol has been more defined as variations within the test procedure have been requested. In order to perform a test that can be publically stated as a DLG PowerMix test the following limitations must be adhered to:

- The driving speed and PTO speed must not be below the respective (no load) speed by a certain margin. If engine power is sufficient, “Eco setting” of PTO drive is allowed
- The number of control valves for the hydraulics are limited
- Tire inflation pressure is set, furthermore, the tires should remain the same throughout the test
- The ballast requirements are stated
- The operating temperatures of the machinery at start of test are stated
- In the case of four wheel drive tractors, four wheel drive should be engaged

If adhering to the PowerMix test protocol, a repeatability of 1-2 g/kWh can be expected according to DLG. DLG does not correct the measured data according to ambient conditions.

In summary, the strengths of the DLG test procedure is that of easy adaptation, proven methodology and acceptance from OEM's.

2.1.2 OEM input

Approximately 2600 people work at the John Deere manufacturing and development centre at Mannheim of which a couple of hundred work in the development area. Their facilities include 3 dynos, of which 2 are used for PTO power tests. A wind tunnel equipped with dynos and hydraulics in order to replicate the PowerMix test procedure is also available. Stationary ECU mapping, emission measurements and thermal management are conducted on a regular basis in the test facilities as are predictive simulation activities. A test track nearby is used for vehicle tests.



Regarding fuel consumption, there are several definitions that need to be clarified. Although it is not the main purpose of this report it is however worthy to mention them. They are:

- If a fleet average fuel consumption requirement is going to be put into effect, how is the “fleet” defined? There are many NRMM applications, some of which use the same vehicle architecture but are used for very different purposes
- As the use of tractors, i.e. the driving pattern varies to a large extent between different regions, how should this be included in the methodology? Is weighing of different parts of the cycle to be used in order to compensate for this?
- Which variants/options should be tested for fuel consumption? Is it the most sold option package for each machine, or is it necessary to widen the investigation to include a variety of option packages? Or should a “worst case” option package be used?

The necessity of an agreement between the industry and government for the above mentioned definitions as well as a joint decision on which test methods to be used is of critical importance. Effort should be made to achieve a test method that is reasonable and which reflects benefits of different designs rather than focusing on what a “real-life” fuel consumption may be. This approach should also be considered for the cycle definitions.

Naturally, a global understanding of how to perform fuel consumption tests for tractors would be ideal, however, there are differences that may not be possible to overcome by simple weighing of results. When comparing the USA market in which throttle is traditionally operated by hand (often wide open) and speed is controlled by gears with the EU market in which pedal-operated throttle is traditionally used (with which a more transient operation for the engine can be expected) the issue becomes more difficult to address. To complicate a global approach even further the use of drawbar power is dominant in the USA while the 3-point hitch is used more frequently in the EU. Also, the transport of tractors is often made by trucks in the USA while in EU tractors are typically transported by driving on the roads.

The main reason for John Deere to be working with the DLG PowerMix test procedure is that it is practical in its approach. Using an in-house test setup can give a valuable insight in current fuel consumption status early in the development phase as well as facilitate optimization prior to a DLG test. It is clear that relevant effects from the auxiliary devices such as hydraulic and transmission losses must be included in a fuel consumption test and so a complete vehicle approach is considered to be necessary.

The exact composition of the test cycles may be subject for discussion, however, the main focus is currently to replicate the DLG PowerMix test cycle



so that there is a correlation of test data. For this purpose John Deere uses a reference tractor that has undergone the PowerMix tests at DLG. The possibility of controlling ambient conditions by use of the wind tunnel is naturally of primary interest, however, at the time of this report, that has yet to be established. The wind tunnel is capable of delivering air flow equivalent to 20 km/h, which is considered to be sufficient as a typical wind speed of 3 km/h has been measured at DLG.

Similarly with the DLG tests, the driver can affect the results, particularly if a manual transmission is used. In the case of an automatic gearbox, the dyno controls any changes in driver input to the gearbox, while in the case of manual transmission the gear changes are done by remote by the dyno operator.

The complete test preparation and procedure is similar to that used by DLG. Initially, a PTO test is performed in order to establish load factor in the cycles. Also, in order to replicate the DLG tests, a model that incorporates the dampening effect of the DLG truck is applied in order to adjust the cycle load for a correlating transient behavior. The test is then performed and the wheel slip and drag effects are accounted for during post-processing.

It is not the ambition of John Deere to develop test procedures using their test setup, rather to follow any standardized cycles used within the industry. Currently the DLG PowerMix procedure is considered by John Deere to be the most practical industry standard available today.

In short, the John Deere approach is a step closer towards controlled condition testing while retaining practical methodology. Discussions concluded that it is more important to achieve a clearly defined standard for fuel consumption testing than to achieve a fuel consumption for real-life use of the machine.

3 SIMULATION STUDIES

3.1 Scope

In this investigation a vehicle performance simulation model of a wheel loader is created in the simulation tool GT-Suite.

A driving cycle is derived, in which the wheel loader is loading sand from a sand pit onto a dumper truck.

Simulations are performed, varying parameters on the driving cycle and on the wheel loader model in order to study their influence on consumed fuel.



3.2 Test/Analysis description

3.2.1 Simulation tool

The simulation package GT-Suite v7.0.0 Release Build 4 is used for these simulations. GT-Suite originates from GT-Power, which is an engine performance simulation tool. It has gradually expanded to enable simulation support in other areas within engine and vehicle development. In v7.0.0 general 2 dimensional and 3 dimensional mechanics and hydraulics has been included. This has enabled GT-Suite to be used for simulation of the fuel consumption of a wheel loader. New functionality in software usually means new bugs and this case has been no exception. After the first release of this report had been sent to the customer for review, the software developer discovered an error in GT-Suite that affects the hydraulics in these simulations. The error has been corrected and the analysis has been rerun. It turned out, however, that this error had relatively small impact on the results.

3.2.2 Simulation model

The simulation model of the wheel loader is limited to two dimensional mechanics to keep complexity down. This means that vertical and backward / forward motion is possible but not sideways motion. Because of this steering of the wheels is excluded from the model, i.e. the wheel loader cannot make a turn.

The model can be divided into four main blocks:

- Engine and drivetrain (engine, transmissions, drive shafts)
- Vehicle (body, wheel axles, wheels)
- Hydraulics (pump, actuators)
- Loader linkage (Arm, links hydraulic cylinders, bucket)

When nothing else is stated data from an existing wheel loader is used in the model

As far as possible data from an existing wheel loader is used in the model. The model may not fully represent the chosen wheel loader, since some data are estimations and some modeling simplifications are made. The model does however represent a possible wheel loader of the same size.

3.2.3 Engine and drivetrain

The engine is map based. This means that it is not a physical model of the engine. Instead it uses previously measured or simulated data in the form of lookup tables (maps) to describe the performance of the engine. In this case the engine model consists of two maps, one that translates the accelerator pedal position to an engine load for each engine speed and one that translates the engine load to fuel consumption for each engine speed. The advantage of a

map based engine model is its low complexity, which means easy implementation and shorter simulation times. The disadvantage is that the accuracy of the model is reduced during transients since it is based on steady state data. Turbo lag and transient fuel strategies are not captured by this model. A rate limiter is applied to the accelerator pedal position as a crude compensation for the lack of turbo lag.

The cooling fan and generator are modeled as power sinks on the engine. Maps translate engine speed to power that is subtracted from the engine output power.

As for the engine the torque converter model uses maps based on measured steady state performance. This gives a good representation of the behavior as the transient effects in a torque converter are small.

The transmission has four gears with the gear ratios from an existing wheel loader. Only the second gear is however used during the dumper loading cycle.

The transmission losses are modeled as a power sink connected to the transmission object. A map translates transmission input shaft speed to power that is subtracted from the transmission output power.

The existing wheel loader has reduction planetary gears in the wheels. These planetary gears does not exist in the model. Instead this is modeled as a reduction gear on the drive shaft. It is shown as differential-1 in Figure 3.

All inertias in the drivetrain are estimations.

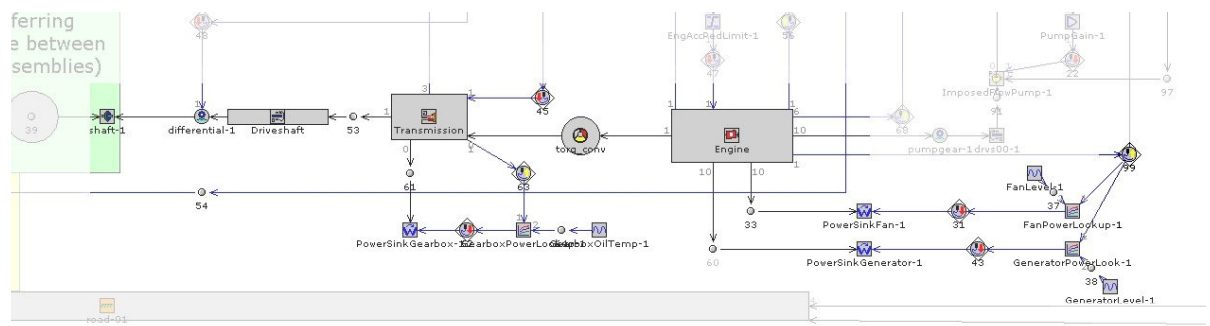


Figure 3, Engine and drivetrain

3.2.4 Vehicle

The vehicle model consists of three bodies: the vehicle body and the two wheel axles.

The vehicle body is given the approximate mass of the wheel loader without loader linkage and wheels. It has the loader linkage and the wheel axles connected to it. The rolling resistance and aerodynamic drag forces are also applied to this body.

The wheel axle bodies are given the moment of inertia and approximate mass of the wheels. They are connected to the ground through rolling connections. The rolling connection does not allow slip, which may affect the accuracy of the model slightly. The wheel planetary gear losses are applied to the wheel axle bodies as power sinks. The drivetrain torque is applied to the rear axle. The torque from the brakes are applied to both axles.

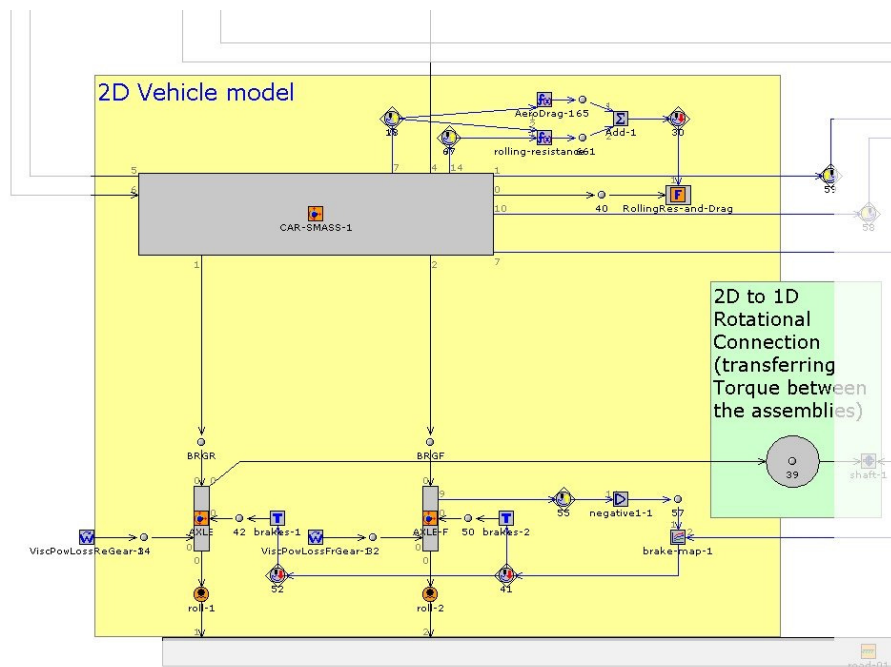


Figure 4, Vehicle

3.2.5 Hydraulics

The hydraulics consists of a feeding circuit connected to the tilt and the lift circuit.

The heart of the hydraulic feeding circuit is a variable displacement pump driven by the engine. As no information is available regarding pump control, its displacement is pressure regulated through a PID-regulator.

The tilt circuit servo valve's two feeding ports are connected to the low and high pressure side of the feeding circuit respectively. Its actuated ports are

connected to each side of the double acting tilt cylinder. It can be actuated in three modes:

1. high pressure feeding port ↔ actuated port1, low pressure feeding port ↔ actuated port2
2. high pressure feeding port ↔ actuated port2, low pressure feeding port ↔ actuated port1
3. no connection between the ports

The lift circuit has the same configuration as the tilt circuit, but its servo valve can also be actuated in a fourth mode called floating mode where both actuated ports are connected to the low pressure feeding port. This mode makes the loader lower to ground by gravity.

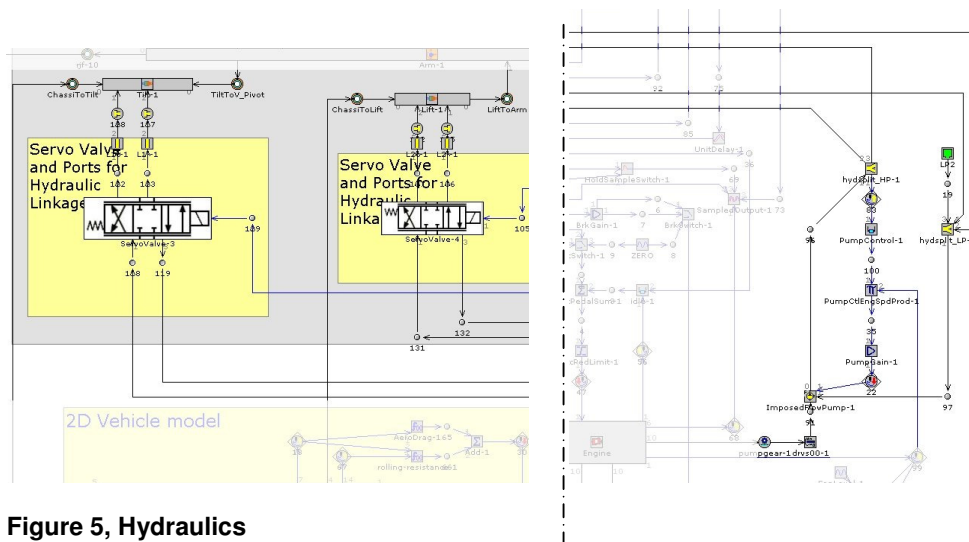


Figure 5, Hydraulics

3.2.6 Loader linkage

The loader linkage consists of five rigid links, a bucket and the lift and tilt hydraulic cylinders connected by rotational joints. It is completely parameterized and a picture of it is shown in Figure 6.

At the bottom of the bucket there are two contact points for bucket to ground contact. This contact is frictionless.

The bucket load is modelled as a force which is dependent on gravity and on the bucket accelerations.

Model instability made it necessary to filter the bucket accelerations in the force calculations. This should however have negligible influence on the simulation results.

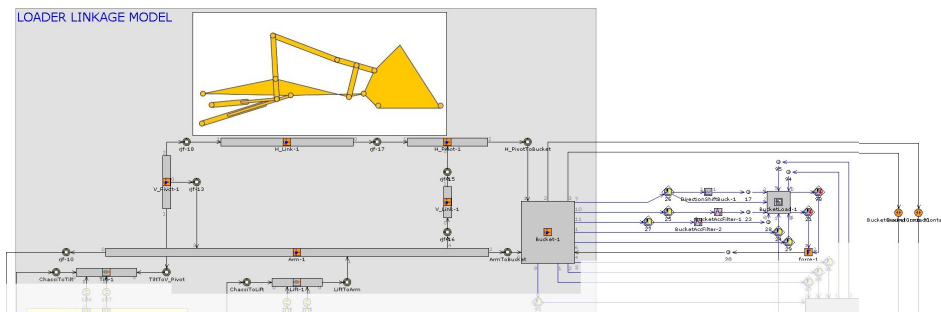


Figure 6, Loader linkage

3.2.7 Driving cycle

In this simulation the wheel loader is to load sand from a sand pit onto a dumper truck. To enable the simulation model to do this a driving cycle control is built that controls the necessary functions of the wheel loader. The functions that need to be controlled are:

- Accelerator pedal position
- Brake pedal position
- Gear
- Bucket vertical position (lift)
- Bucket angle (tilt)
-

The driving cycle to control these functions is built up from a number of consecutive events. The events of the base cycle are explained below.

1. Start with bucket at 0.5 m, 43°
2. In 5 m accelerate from 0 to 10.5 km/h. Set lift to floating mode and tilt bucket to 0°.
3. Maintain 10.5 km/h for 15 m.
4. Decelerate to 0 km/h in 5 m.
5. Keep in forward gear, increase engine speed to 1850 rpm for 5 s while braking to simulate the interaction with the sand pit. Tilt bucket to 43° and apply bucket load (8722 kg).
6. When bucket is tilted, lift bucket to 0.5 m.
7. In 5 m accelerate backward to 10.5 km/h.
8. Maintain 10.5 km/h for 15 m.
9. Decelerate to 0 km/h in 5 m.
10. In 5 m accelerate forward to 10.5 km/h. Lift bucket to 3.7 m.
11. Maintain 10.5 km/h for 15 m.
12. Decelerate to 0 km/h in 5 m.



13. Tilt bucket to -49° and release bucket load.
14. Tilt bucket to 43°
15. In 5 m accelerate backward to 10.5 km/h. Lower bucket to 0.5 m.
16. Maintain 10.5 km/h for 15 m.
17. Decelerate to 0 km/h in 5 m.

Due to that the model is limited to two dimensions the driving cycle cannot include any turning of the vehicle. The energy required to turn the vehicle is however considered very small compared to the total energy consumption.

3.2.8 Parameter study

In order to study to what extent changes to the model and the driving cycle affect consumed fuel a parameter study is performed. The chosen parameters are:

- **Wheel loader acceleration/deceleration:** It affects event 2, 4, 7, 9, 10, 12, 15 and 17 in the driving cycle, and its aim is to capture effects of soft vs. aggressive driving style
- **Bucket lift height:** It affects event 10 in the driving cycle.
- **Engine speed when driving into the sand pit:** It affects event 5 in the driving cycle and its aim is to capture effects of the interaction between wheel loader and sandpit.
- **Hydraulic pump efficiency:** It affects event 2, 5, 6, 10, 13, 14 and 15 in the driving cycle
- **Total distance from rear turning point to loading/dumping position:** It affects event 3, 8, 11 and 16 in the driving cycle
- **Bucket load:** constant or varying according to cycle
- **Tire rolling resistance**

In the study it is assumed that that all responses are linear. Because of this a full factor analysis of two levels is setup. With 7 parameters this means $2^7=128$ cases with different parameter variations. This enables studying the effect of each parameter individually as well as the interaction effects between the parameters. The low and high value of each parameter is shown in Table 1.

Table 1, Parameter values

Value\ Parameter	Acceleration [m/s ²]	Lift height [m]	Sand pit engine speed [rpm]	Pump efficiency [%]	Total distance [m]	Bucket load [-]	Rolling resistance [-]
Low	0.425347	3.2	450	50	25	Constant	0.02
High	0.850694	3.7	1850	100	50	Varying	0.04
reference	0.6380205	3.45	1150	75	37.5	Constant	0.03

3.2.9 Driver behavior

An attempt is made to simulate two drivers with different behaviors. Driver 1 controls the vehicle deceleration using the brakes while driver 2 controls the vehicle deceleration by reversing the gear and using the accelerator.

3.3 Results

3.3.1 Parameter study

Figure 7 shows the effects on cycle fuel consumption and Figure 8 shows the effects on cycle time. The plots show the effect of a change from the parameter reference value to the max value according to Table 1. The error bars in Figure 7 and Figure 8 represent a 95% confidence interval. This does not say anything about the validity of the simulation it self. Instead it measures how well this linear approximation of the results describes the actual results from all cases in the study (128 cases, Table 1). The error will increase if there are a large number of factors that are outside of control in the study. The error will also increase if the study fails to include all effects of the parameter variation in the results, e.g. interaction effects between the parameters exist that are not taken into account in the study. An error bar larger than the effect it self means that there is less then 95% confidence in that the parameter has any impact on the result.

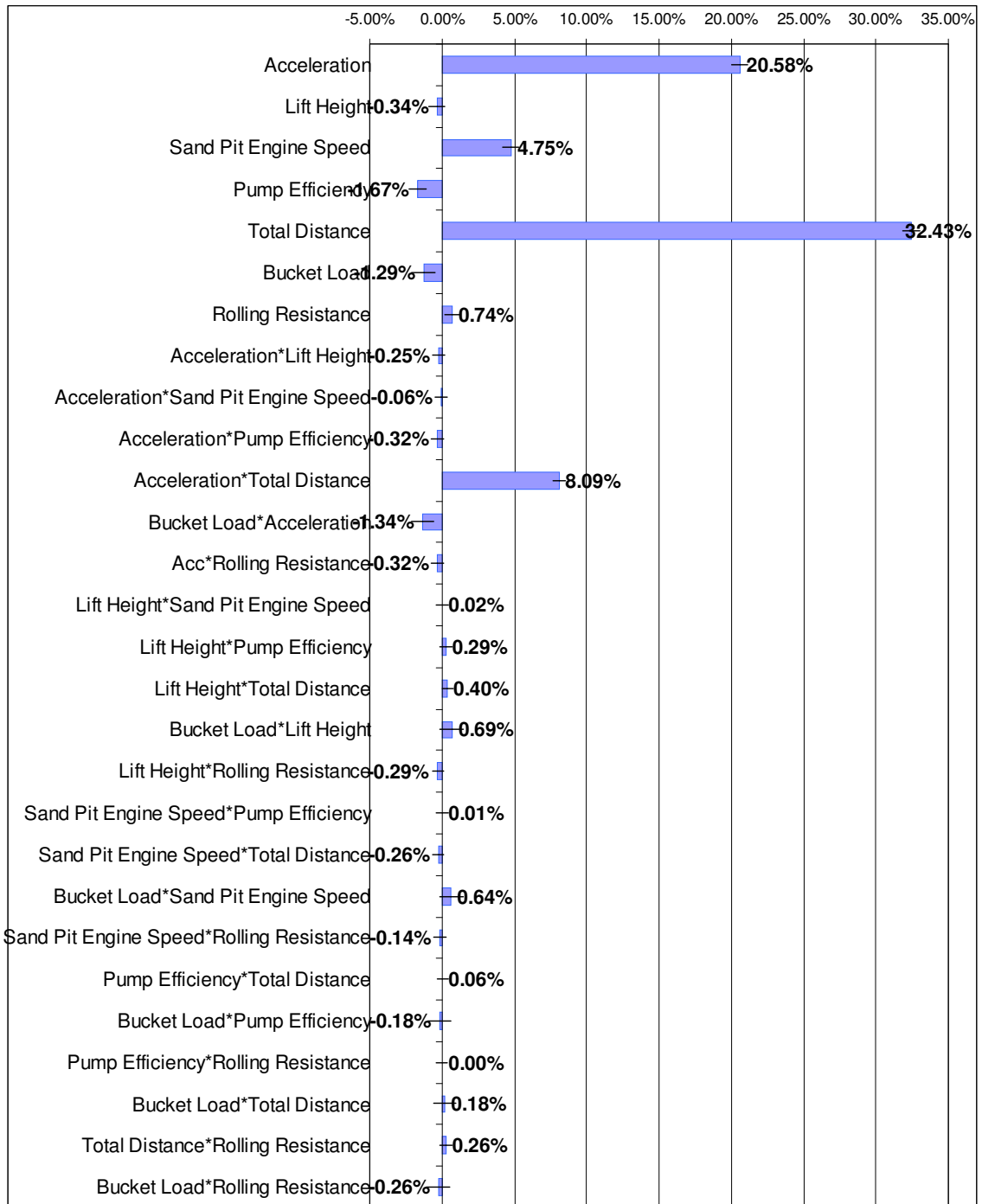


Figure 7, Effects on cycle fuel consumption

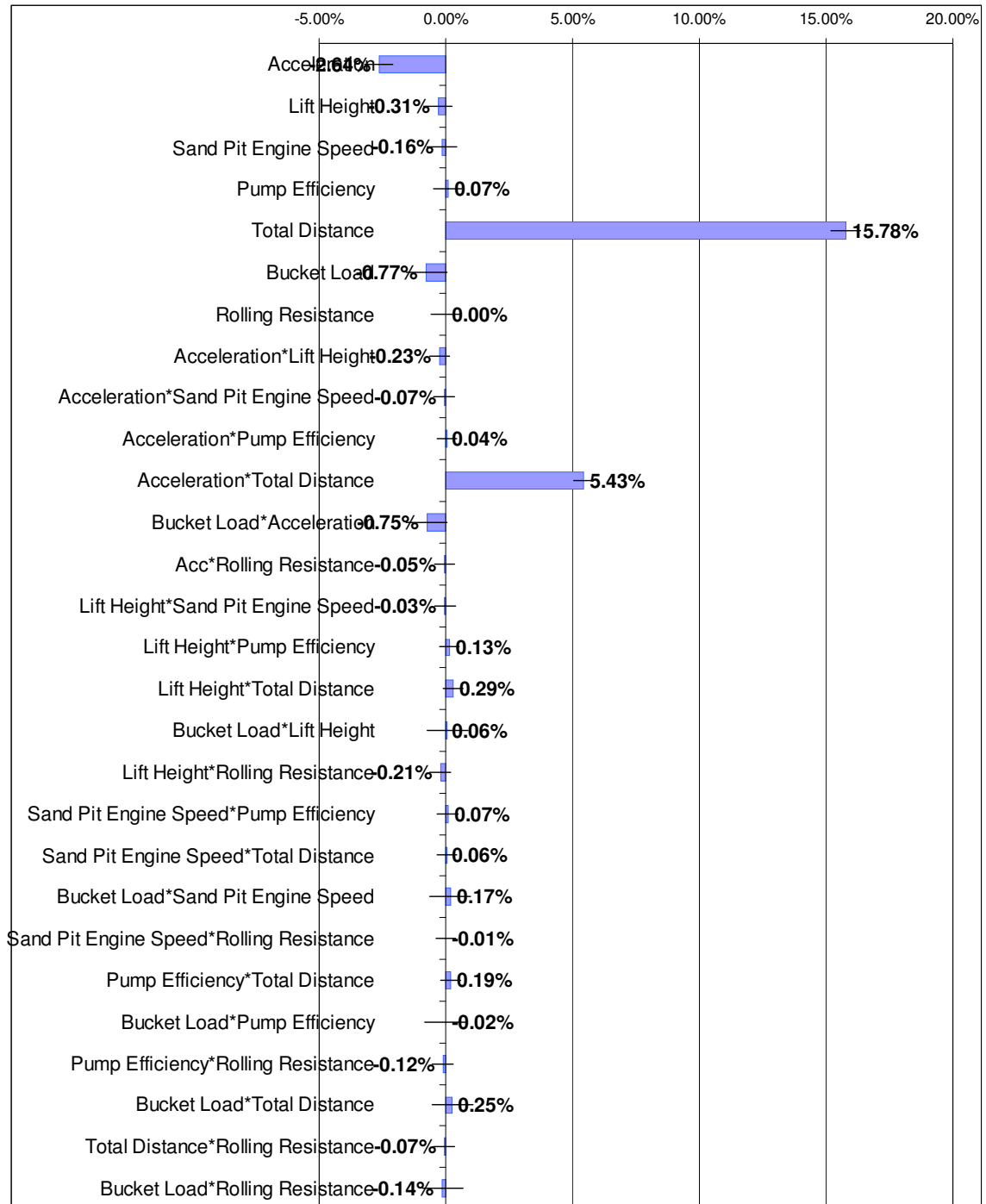


Figure 8, Effects on cycle time.



3.3.2 Driver behavior

The driver behavior analysis failed to produce reliable results as driver 2 was not able to follow the driving cycle accurately enough with the currently modeled vehicle speed control system.

3.4 Conclusions

The presented results are valid for the modeled wheel loader and for the chosen driving cycle, but the model and driving cycle has not been calibrated to measurements, so for full confidence the results have to be confirmed by tests with a real wheel loader.

3.4.1 Parameter study

Total distance and acceleration has the biggest influence on the fuel consumption of all the investigated parameters. Increased transport distance or more aggressive acceleration/deceleration increases the fuel consumption significantly. There is also an interaction effect meaning that a longer transport distance increases the influence of the acceleration and vice versa.

The sand pit engine speed also has significance on the fuel consumption. Increased sand pit engine speed increases the fuel consumption. This crude way to simulate the interaction between wheel loader and sand pit indicates that higher resistance (friction) in the sand pit increases the fuel consumption.

Pump efficiency and bucket load (constant or varying) has rather low impact on the fuel consumption, but constant bucket load increases it and high pump efficiency reduces it. There is however an interaction effect between acceleration and bucket load meaning that more aggressive acceleration together with constant bucket load gives an additional increase in fuel consumption.

The lowest influence on the fuel consumption comes from the rolling resistance and the bucket lift height. The low influence of the rolling resistance indicates that the ground surface material and the choice of tires are of lower importance when it comes to the fuel consumption in this cycle. Higher rolling resistance only increases it slightly. The confidence in the influence of the bucket lift height is low, and as the results indicate that higher bucket lift height actually reduces the fuel consumption, the effects of this parameter should probably be ignored.

The only two parameters that have any significant influence on cycle time are total distance and acceleration. Not surprisingly long total distance increases it and high acceleration decreases it.

To summarize; this study indicates that total cycle distance and vehicle acceleration/deceleration has the highest impact on the cycle fuel consumption. Sand pit resistance, or how hard the driver pushes into the pit also have impact on the cycle fuel consumption. The efficiency of the hydraulics and how high the



bucket load has to be lifted have low impact on the cycle fuel consumption. So does the rolling resistance, meaning that the ground surface material and choice of tires are rather unimportant. Using a constant bucket load vs. actually loading and dumping the load also has low impact on the cycle fuel consumption, but its impact is amplified by reduced hydraulic efficiency, increased total distance or reduced bucket lift height.

3.4.2 Driver behavior

Although no reliable results were produced regarding driver behavior, the simulations indicate that the difference in fuel consumption between the two drivers is small. No definite conclusions can however be drawn without rerunning the simulation with a vehicle speed control system that enables driver 2 to follow the driving cycle more accurately.

3.5 Discussion

3.5.1 Sandpit interaction

In this analysis the interaction between sandpit and wheel loader is greatly simplified. When the wheel loader is driving into the sandpit a break torque is applied to the wheels. The engine speed is increased to simulate the loader working its way into the sand and filling the bucket. A vertical force is then applied to the bucket representing the added sand load. The engine speed increase is varied to simulate different sand resistance or driver aggressiveness. This is a simple way to simulate the effects of changes in this interaction. It does however not give any specific information about the effects of e.g. the sand resistance. The interaction between sandpit and wheel loader is complex and depends on:

- Sand quality (e.g. material composition, moist content, grain size and structure)
- Sandpit geometrical shape
- Bucket size and shape
- Bucket lift and pitch during loading (digging hard into the sandpit or just scraping the surface)
- Vehicle speed
- Engine speed
- Etc.

To get information about effects of e.g. sand quality measurements are necessary to collect data about the resistance in different sand qualities and statistics from bucket loading events from which to generate a normalized loading event.



4 OTHER DATA

4.1 PEMS testing

AVL MTC has, on commission by the Swedish Road Administration tested a number of heavy-duty vehicles on road using PEMS equipment (Portable Emission Measurement System). In this section the brake specific fuel consumption from some of these vehicles has been compared to the certification/type approval data (ETC) for the engine supplied by the manufacturer.

The reason for including this data for heavy duty vehicles, which is not NRMM, is to give additional background to the issue of discrepancies between certification results versus in-use results. Similar discussions are currently ongoing in the light duty segment regarding the real life emissions from the 120g CO₂/km vehicles.

The vehicles presented in this section have been tested at driving conditions and loads representing a normal working day for each vehicle based on data from the vehicle owner. Commercially available Environmental class 1 diesel (MK1) has been used and no services have been performed prior to the testing.

Vehicle number 1 was a Volvo FH480 (Euro IV) equipped with a SCR system, used for loading and transporting of timber. It was tested in winter time (snowy conditions) at an average ambient temperature of -5°C. The test route was divided into driving without load at curb weight (21,2 tons), idling (loading), and driving with maximum load (60 tons).

Vehicle 1	Unloaded	Idling and loading	Maximum load	Engine certification data
Fc [g/kWh]	181	255	183	202
Fc [l/100km]	49	-	84	

Vehicle number 2 was a Scania R420 (Euro IV) equipped with EGR used for paper distribution. It was driven from Jordbro through road 73 towards Stockholm down to Södrälänken and up to E4 going south. The vehicle returned the same way after passing Skärholmen. The test route was performed 3 times.



The time for test number 1 is 20 minutes longer than for test number 2 and 3 due to a traffic jam. The test temperature ranged between +1 to +4 °C.

Vehicle 2	Test 1	Test 2	Test 3	Engine certification data
Fc [g/kWh]	342	270	290	213
Fc [l/100km]	55	52	52	

Vehicle number 3 was a Scania R420 (Euro IV) equipped with EGR (same type of engine as vehicle number 2) used as a sludge tanker. It was driven empty from Kallhäll through motorway and suburban roads to Bromma followed by idling (sludge pumping). Unfortunately the ECU-signal was lost (no kWh-values) for the return trip to Kallhäll. The test temperature ranged between +1 to +4 °C.

Vehicle 3	Route 1	Idling and sludge pumping	Engine certification data
Fc [g/kWh]	84	53	213
Fc [l/100km]	30	-	

The above presented data show some discrepancy between stated fuel consumption and in-use measurements. The emission test method, ISO 8178, for heavy duty is currently the same as used for NRMM, and it is not unlikely that there will be a difference between certification data and in-use data for NRMM as well. This is however not quantified in this investigation.

5 CONCLUSIONS

In the case of methodology for fuel consumption measurements for tractors, no conclusions can be drawn yet as to how much variations in ambient conditions effect the results. Input for this may come in the relatively near future, as it is being looked into. The DLG approach is by many considered to be the best method available and has to some extent become an unofficial industrial standard for testing tractor fuel consumption. A close supervision of test conditions must however be maintained as is clear by the number of limitations that is stated by DLG for the test to be considered to be according to the PowerMix test method. In addition to this, there are some obvious limitations concerning ambient conditions related to the outdoor track, for instance the test cannot be performed when raining.



Simulations show that wheel loader fuel consumption test methodology is mostly dependant on distance in the cycle, acceleration rate within the cycle (aggressiveness of the driver) and to some extent the gravel interaction with the bucket (sand pit engine speed). Surprisingly, bucket load variations has a lower impact than expected, suggesting that if necessary, a fixed bucket load may be used (as in the JCMAS H022 method). However, this will also remove the sand pit engine speed effect. It should be noted that the aggressiveness of the driver (i.e. the acceleration rate of the vehicle) is clearly defined in the JCMAS test method. This indicates that similar conclusions have been drawn in the development of that cycle as those obtained from these simulations.

6 RECOMMENDATIONS

Until results are available to indicate the effect of ambient conditions on tractor fuel consumption it is unclear whether the DLG PowerMix test setup is suitable as a certification method. While being the best methodology publically available today, this factor must be taken into consideration. Work is in progress concerning this aspect and it may be worthwhile to follow up on these activities. A deeper theoretical investigation relating to the effects of ambient conditions may also be conducted, however it may be difficult to fully take into account all the possible variations as test results show.

The simulation investigating the cycle build-up for a wheel loader should preferably be looped with test data in order to grade results on an absolute level. The scope of this investigation did not allow for a deeper investigation concerning the possibility to replace actual tests altogether using simulation methods, however, it is clear that even though the simulation tools exist this approach is not possible until a higher level of maturity is established.

With the interesting indications obtained from the wheel loader simulations, it would be worthwhile to perform a similar study of an excavator. Comparisons could be made with existing methods, such as the JCMAS H020 excavator test cycle.

7 REFERENCES

7.1 Literature

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7.2 Personal communication

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[3] *Visit at John Deere in Mannheim, Dr. Back and Dr. Kunz*

[4] *Telephone call, Dr. Peter Back*

[5] *Meeting at VCE, Lennarth Zander, Group Manager Simulations*

8 NOMENCLATURE

DLG, Deutsche Landwirtschafts-Gesellschaft (German Agricultural Society)

EU, European Union

ISO, International Organization of Standardization

JCMAS, Japan Construction Mechanization Association Standard

NRMM, Non-Road Mobile Machinery

OECD, Organization for Economic Co-operation and Development

OEM, Original Equipment Manufacturer

PLU, Displacement type flow meter

PTO, Power Take-Off

USA, United States of America

VCE, Volvo Construction Equipment