
AMMONIA AS CARBON FREE FUEL FOR INTERNAL COMBUSTION ENGINE DRIVEN AGRICULTURAL VEHICLE

ACTIVATE

Work Package 5
Deliverable Report

Topic: D5.3
REPORT FROM TRACTOR CALIBRATION.

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1 Adaptation of an agricultural tractor for dual-fuel operation using NH_3

An analysis of commercially available orchard tractors was carried out to demonstrate ACTIVATE technology in a real agricultural vehicle. A vehicle was selected whose design allows components to be safely modified and adapted to accommodate an ammonia-fuelled engine with a biofuel and ammonia supply system. Figure 1 shows the overall dimensions of the selected SCOUT tractor, the values of which are summarised in Table 1. This table also provides information on the transmission system.

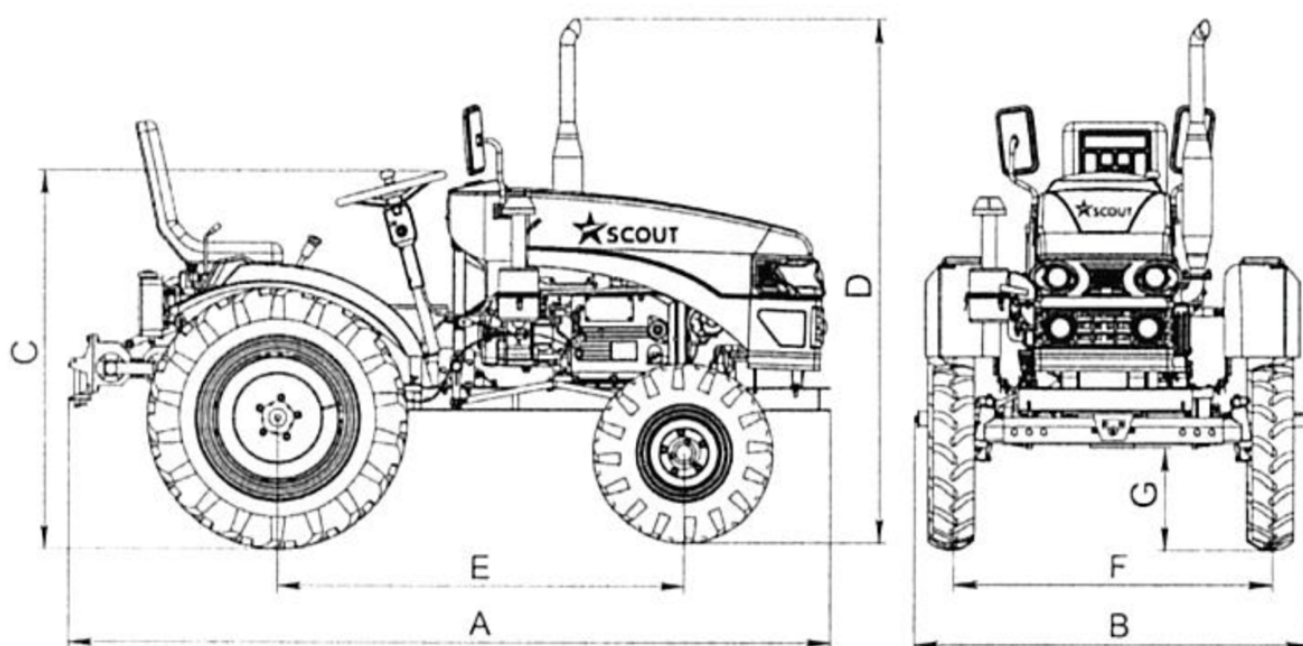


Figure 1: Major dimensions of the SCOUT tractor

Table 1: Selected data on the SCOUT tractor

Main dimensions, mm	A (length)	2415
	B (width)	1350
	C (height by steering wheel)	1190
	D (height by silencer)	1770
	E (wheelbase)	1770
	F (distance between drive wheels)	1090-1300
	G (road clearance)	260
Wheel dimensions, in	front	5"-10"
	rear	6,5"-16"
Unladen weight, kg	540	
Clutch	multi-disc dry, flanged	
Gearbox	manual (3 front, 1 rear) x 2	
Translations (front - from the crankshaft to the drive wheels)	G1	145/1
	G2	95/1
	G3	60/1
	G4	35/1
	G5	25/1
	G6	15/1
Transmission	2 x V-belt	B3048 type

On the SCOUT tractor, the power transfer from the combustion engine to the gearbox is via a V-belt. This type of solution makes it possible, with little interference with the tractor's design, to replace the original tractor engine with a LIFAN engine that has been adapted to run on ammonia as part of the WP2 work package. A schematic drawing of the tractor's transmission system is shown in Figure 2. The tractor's original shaft-mounted pulley (position 2 on Figure 2) has been replaced by a new pulley with a geometry that allows the attachment of additional components such as a signal wheel and a common rail pump drive wheel around it.

In Figure 2 the marked items are: 1. Engine crankshaft, 2. Engine V-belt pulley, 3. Belt drive, 4. Clutch with gearbox pulley, 5. Gearbox input shaft, 6. Hydraulic pump coupling, 7. Reverse gear shaft, 8. Gearbox intermediate shaft, 9. Gearbox main drive shaft, 10. Differential shaft, 11. Final drive, 12. Drive wheel axle shaft, 13. Rear drive wheel.

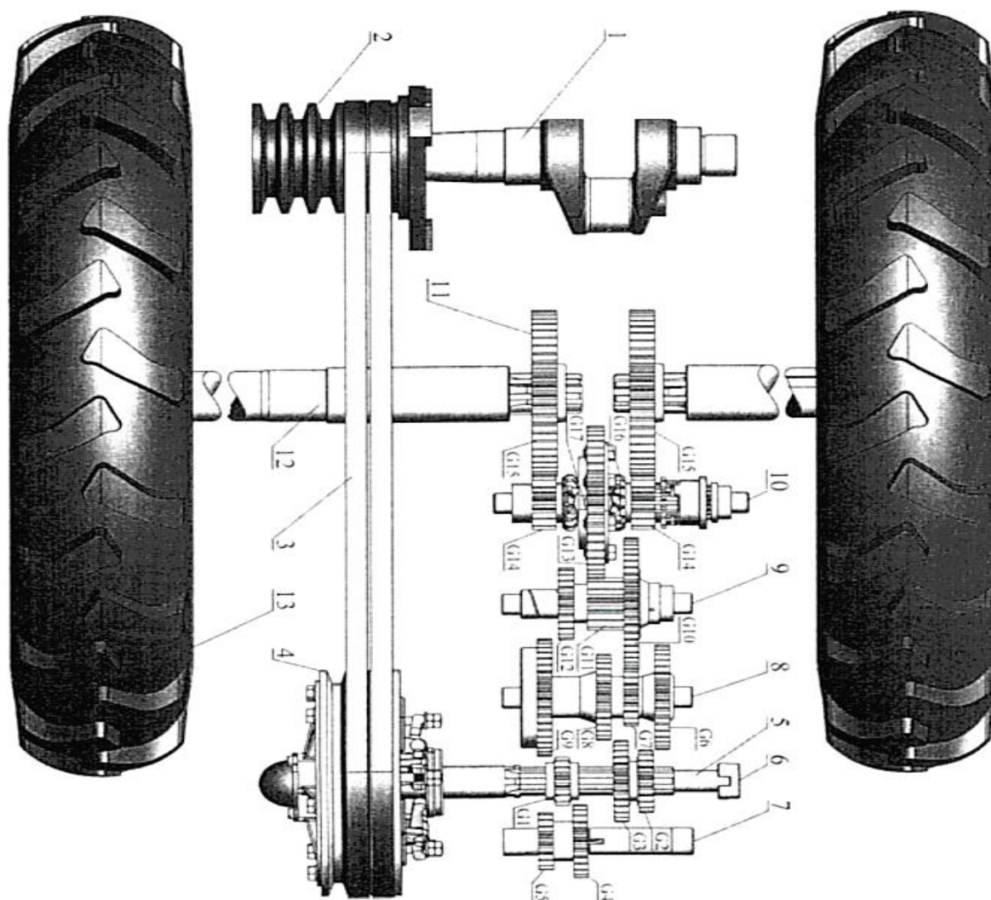


Figure 2: Characteristics of the SCOUT tractor transmission system

The GDI injectors tested and used to direct ammonia injection into the engine cylinder have a certain technical limitation. The nozzle holes are intended for gasoline, which has a calorific value comparable to that of diesel oil and approximately 15% higher than that of biodiesel. In GDI systems, gasoline is injected into the cylinder most often at a pressure of approximately 200 bar. However, the ammonia injection system used in this project can be operated with a maximum pressure of 150 bar. Since the calorific value of ammonia is twice as low as that of biodiesel (i.e. the fuel to be replaced with ammonia), it is necessary to supply much larger doses of this fuel to obtain a similar output power of the engine as when powered by biodiesel. Additionally, lower ammonia injection pressure requires a longer injection duration. In turn, the total injection time is limited by the duration of the working cycle, which in turn is determined by the engine speed. Stable operation of the LIFAN engine in the ammonia fuel mode with a pilot dose of biodiesel is possible in the engine speed range from 1000 to 3000 rpm. The dependence of the LIFAN engine speed on the SCOUT tractor wheel speed for all of the gearbox gear ratios is shown in Figure 3. In turn, Figure 4 shows the power demand on the internal combustion engine shaft depending on the driving speed of the tractor without a trailer and auxiliary devices.

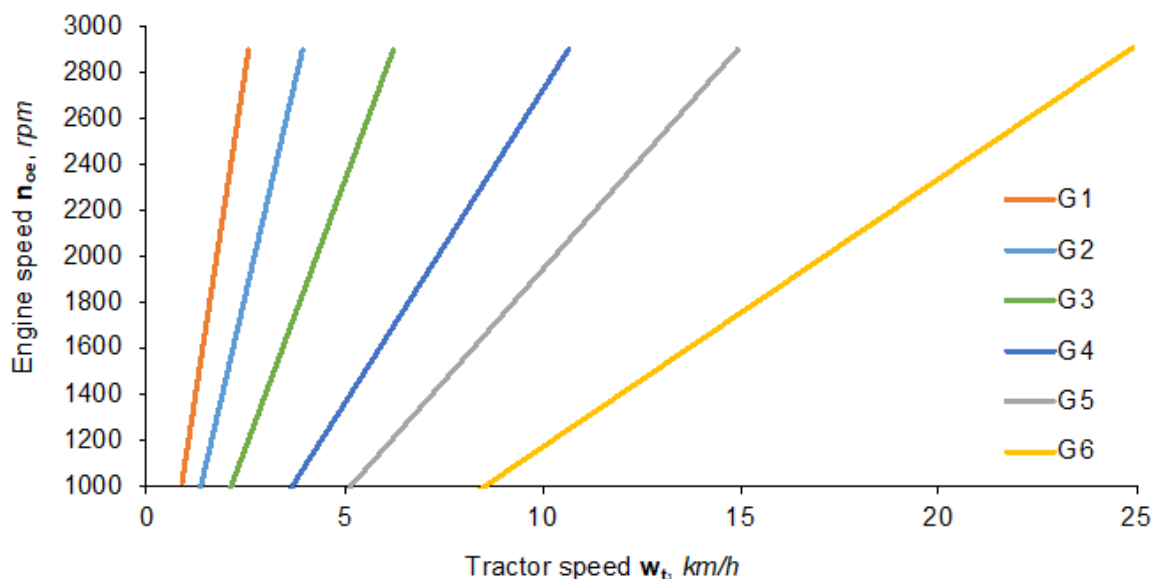


Figure 3: The influence of gear ratios on the relations between engine and tractor wheels speed

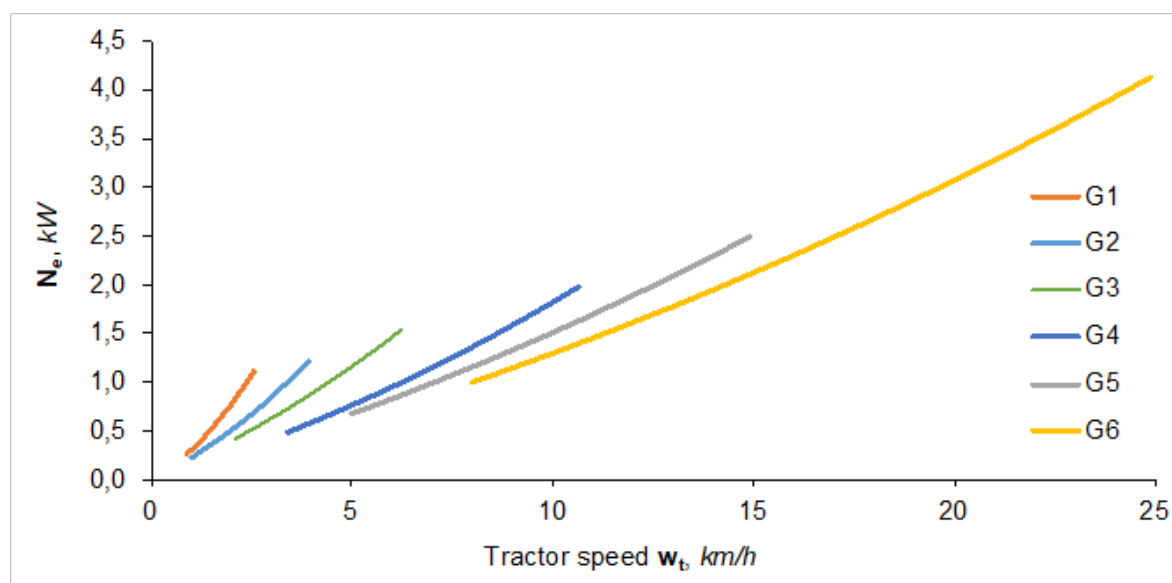


Figure 4: Power demand on the engine shaft vs tractor speed

Figure 5 presents the results of power and torque of the LIFAN engine when powered by biodiesel. The tests were carried out in the range of changes in engine speed at which it is possible to feed the engine with ammonia and a pilot dose of biodiesel. Based on the energy characteristics of the LIFAN engine and the tractor's energy demand, it can be concluded that the engine has the necessary power supply to drive the tractor.

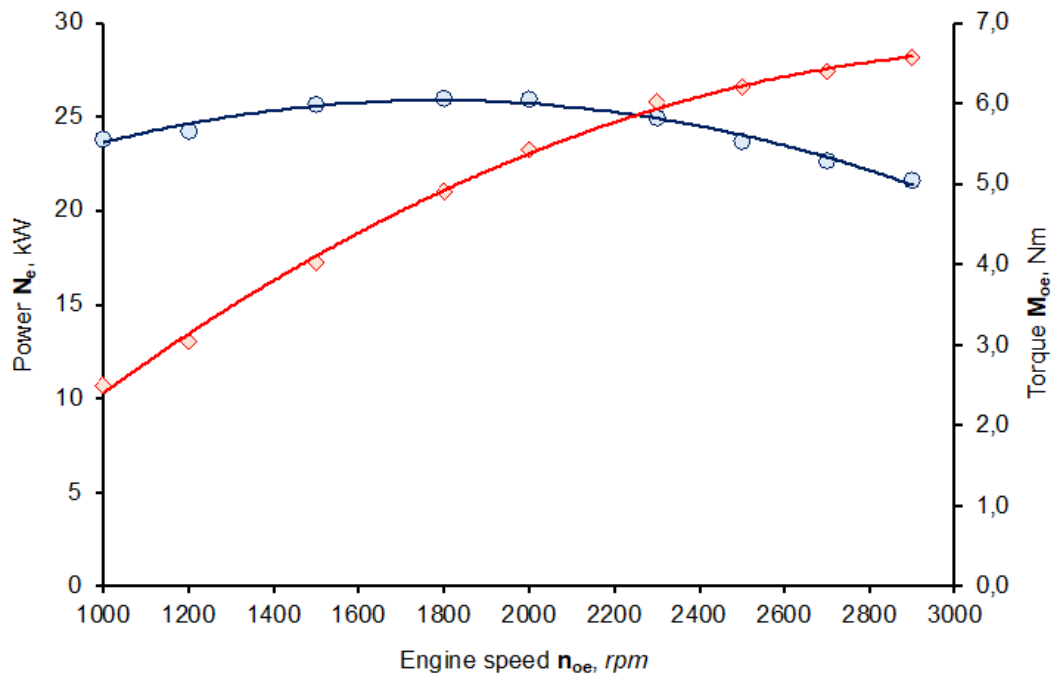


Figure 5: Power and torque of the LIFAN engine fuelled with biodiesel in the range of crankshaft speed changes

Taking into account that most orchard operations are performed at the tractor's speed below 10 km/h, the LIFAN engine has sufficient power reserve to move the tractor with accessories such as a trailer or a sprayer.

1.1 Adaptation of the tractor drive system to run on ammonia

The developed solutions of the ammonia feeding system for the LIFAN engine, which were tested on the laboratory bench, required certain modifications to be transferred to the tractor. A simplified and more compact fuel line has been developed to supply ammonia to the internal combustion engine. The ammonia supply system line is characterized by lower weight and dimensions compared to the laboratory version. This solution uses an ammonia tank with a volume of 10 dm³. The ammonia cylinder is equipped with a double valve that allows the liquid phase to be drawn from one spigot and nitrogen to be added to the cylinder through the other spigot. As in the laboratory system solution, high-pressure nitrogen is used to pressurize ammonia to 100 bar. The liquid ammonia is then supplied to the engine fuel rail via a flexible high-pressure line. The fuel line has mechanical valves and a solenoid safety valve to prevent uncontrolled discharge of ammonia into the environment. Figure 6 shows a view of the fuel line during trial tests in the laboratory. Ultimately, a nitrogen tank with a similar capacity (of about 10 dm³) will be placed next to the ammonia tank. The nitrogen tank is equipped with a pressure regulator to stabilise the pressure at the expected 100 bar. In addition, the system is equipped with a pressure gauge indicating the current pressure in the fuel line.



Figure 6: Ammonia supply line for the tractor engine

Figure 7 shows a common rail with an injector for feeding the engine with a pilot dose of biodiesel and a GDI injector for ammonia injection seated on the head of an internal combustion engine.

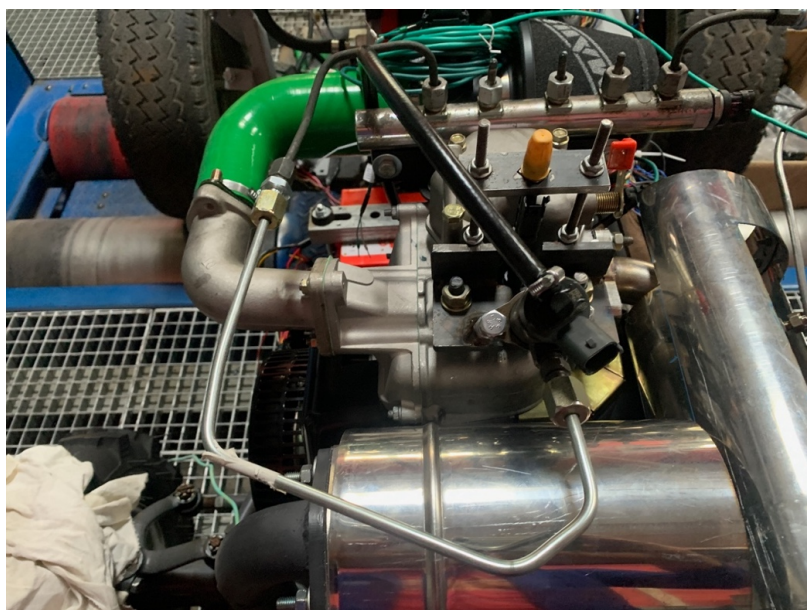


Figure 7: View of biodiesel and ammonia injectors mounted on the engine head

The exhaust manifold was shielded by a screen made of stainless steel. The use of this shield re-

duces the thermal impact from the engine exhaust system on fuel injection components, i.e. biodiesel and ammonia. In addition, the exhaust manifold is equipped with a flue gas intake port and a thermocouple to measure the flue gas temperature (figure 8).

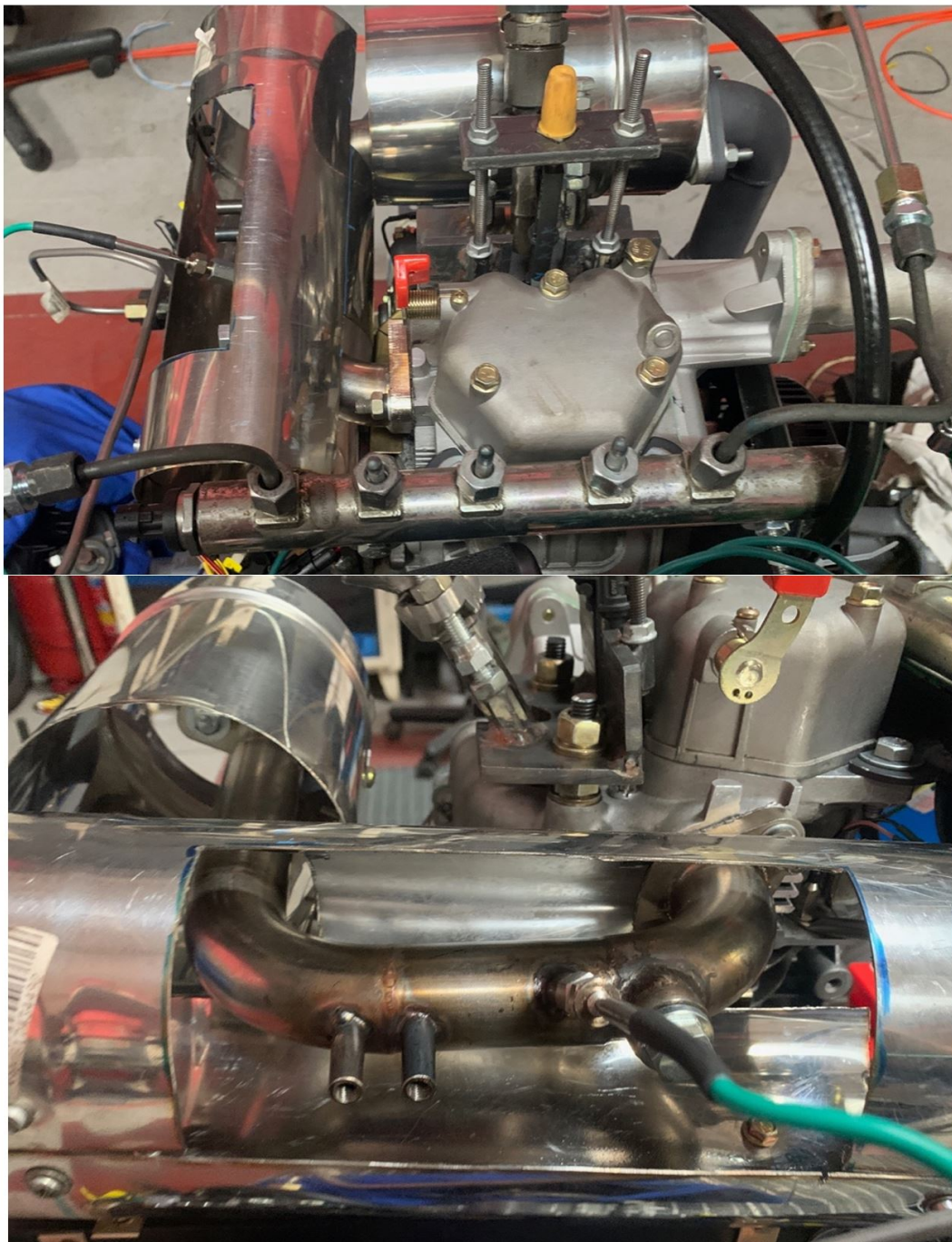


Figure 8: View of biodiesel and ammonia injectors mounted on the engine head

Figure 8 View of biodiesel and ammonia injectors mounted on the engine head
The tracts are equipped with additional components that allow the injection of a pilot dose of

biodiesel using a common-rail system. To reduce the temperature of the biodiesel from the return line to the fuel tank during engine operation, a fuel heat exchanger equipped with an electronically controlled fan is used. A view of the biodiesel supply system components is shown in Figure 9.



Figure 9: The components of the biodiesel supply system

As mentioned earlier, the original pulley for the transmission from the engine to the tractor gearbox was replaced by a new taper lock pulley. This modification was necessary to provide drive to the common rail pump and to mount o the signal wheel for the piston position sensor in the

cylinder. Figure 10 shows the components of the transmission system with the taper lock pulley, signal wheel and common rail pump.

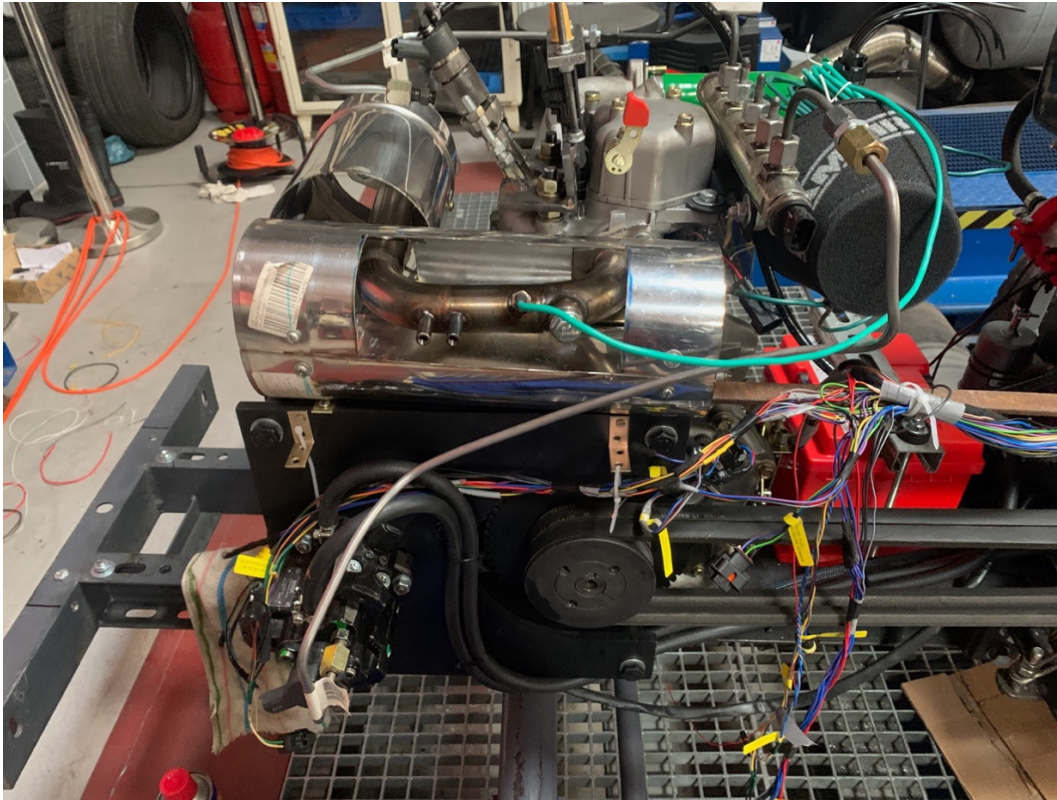


Figure 10: View on the transmission system with the taper lock pulley

An electrical harness with connectors to connect the injectors and necessary sensors was made to connect the electronic control units of the combustion engine. The ECUs were mounted on a metal plate with vibration isolators to reduce the transmission of vibrations from the tractor (Figure 11 left side). The control of the fuel dose by the ECU used in modified engine is via the electronic accelerator pedal (Figure 11 right side). For this reason, the original mechanical accelerator pedal has been replaced by a pedal that generates an electronic signal appropriate to that required by the ECU.



Figure 11: View on the engine ECUs and electronic accelerator pedal

2 Testing of an agricultural tractor during dual-fuel operation using NH_3

Tests on the prototype tractor were carried out on a chassis dynamometer using the measurement infrastructure used during tests on an engine dynamometer. The tractor drive wheels have been fitted with flat tyres to maintain good tyre grip on the chassis dynamometer rollers. Figure 12 shows a view of the tractor on the chassis dynamometer with modified components to allow the internal combustion engine to be fed with ammonia with a pilot dose of biodiesel. Initially, tests were carried out on the installed tractor components to ensure that they were working correctly. On the first attempt to start the engine, a leak was located where the biodiesel injector was seated in the head. The cause of the leak was misalignment between the injector and the hole in the engine head. After fabricating a new piece to press the injector against the engine head, the problem was resolved.

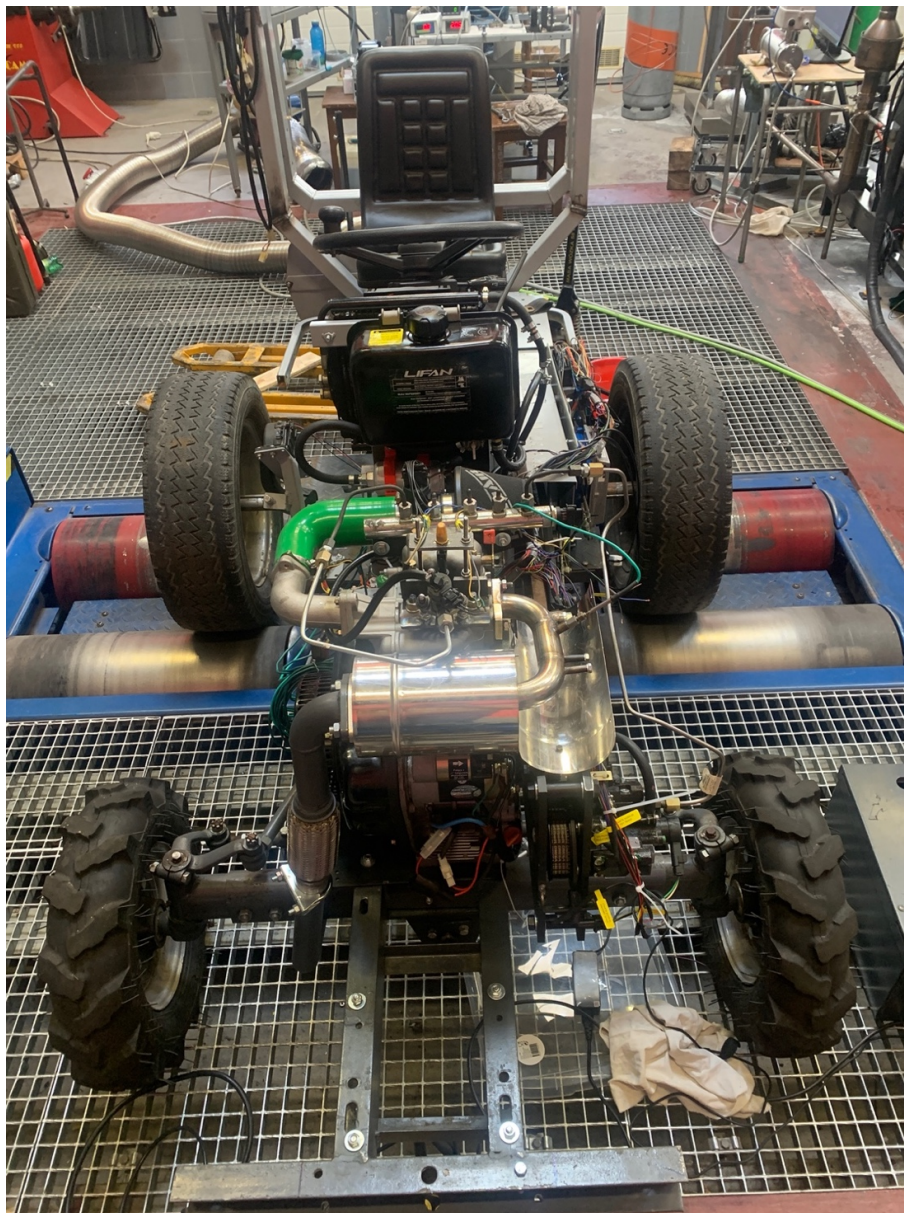


Figure 12: View on the modified tractor

Following tests to check the correct functioning of the various components of the systems fitted to the tractor, parameterisation of the ECU was carried out. Parameter settings were introduced for the crankshaft position sensor and accelerator pedal, and sensor characteristics were implemented for the common-rail pressure, engine temperature and fuel injectors. The biodiesel injection mapping then proceeded. First, the procedure for starting the engine from a cold state was developed. Subsequently, parameters were set to protect the engine from exceeding the maximum speed. Figure 13 shows the dialog box of the ECU managing the operation of the common-rail system when carrying out map calibration for biodiesel.

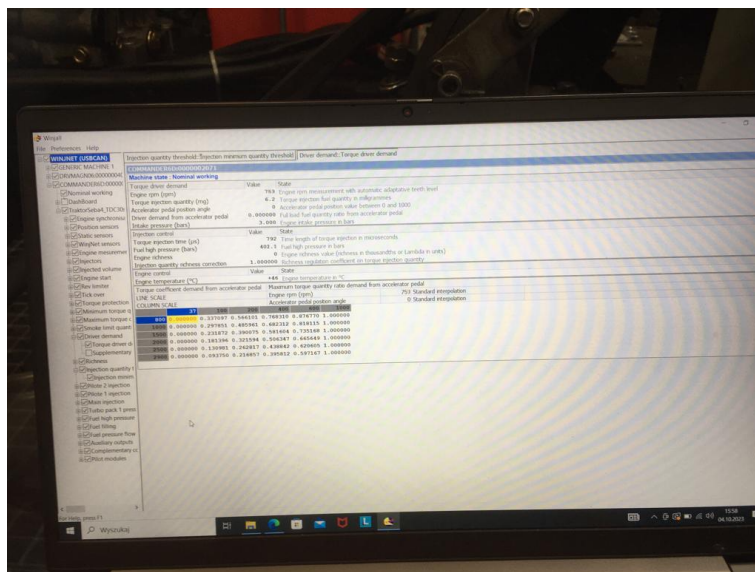


Figure 13: View of Winjall dialogue box of ECU software

Tractor tests on the chassis dynamometer (LPS3000 type) were carried out in load simulation mode (Figure 14). This mode allows the selection of a specific value for the speed of the vehicle on the dynamometer. During the tests, the dynamometer control system controls the speed of rotation of the rollers, keeping the speed of the tractor at a preset level regardless of the position of the accelerator pedal.

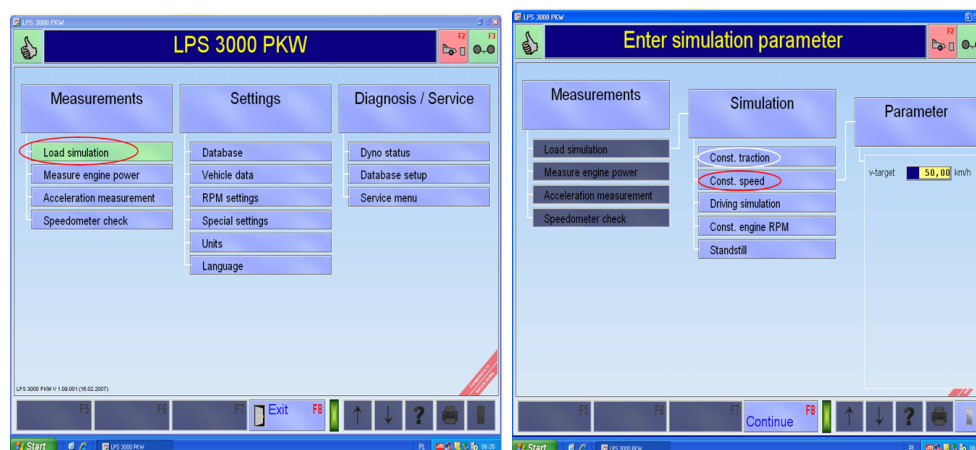


Figure 14: View of LPS3000 software dialogue box - operating mode selection

Figure 15 shows the LPS3000 software dialog box with the parameters whose values were displayed during the tests. Based on the measurements, the system displays the values "F" - tractive effort, "P" - power at the wheels of the tractor, the speed of the internal combustion engine and the speed of the tractor.

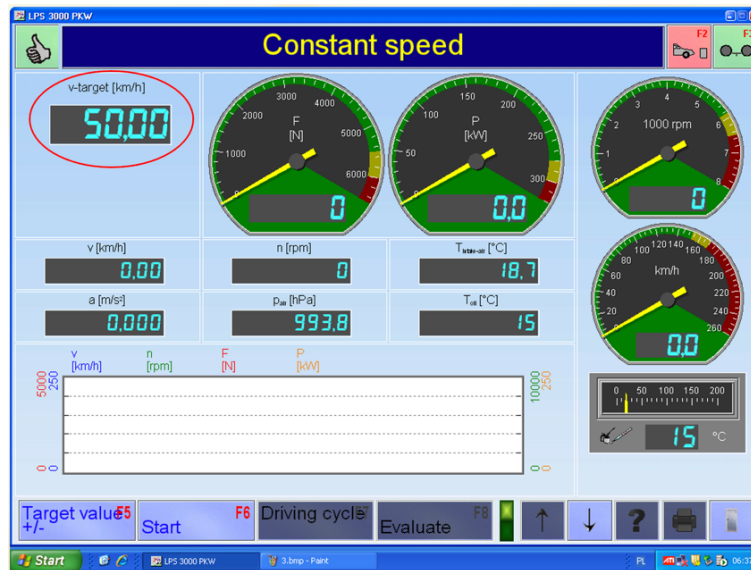


Figure 15: View of LPS3000 software dialogue box - parameters measured by the dynamometer system

The dynamometer mode used in the experimental study allows the internal combustion engine to be tested at constant speed in the variable load range. By changing the position of the tractor's accelerator pedal, the fuel dosage (biodiesel and ammonia) changes according to the injection map implemented in the controller.

3 Determination of the tractor performance under actual operating conditions

Using a chassis dynamometer, tests were carried out on the tractor under actual operating conditions, i.e. at different internal combustion engine speeds and gear ratios. In addition, using the measurement data obtained from the internal combustion engine tests on the engine dynamometer, an energy analysis of the transmission system was carried out. The tests were carried out in such a way that the power generated at the wheels of the tractor corresponded to the value resulting from the vehicle's current resistance to movement on a flat dirt road. The internal combustion engine was fuelled with ammonia with a pilot dose of biodiesel. The relationship between the amount of ammonia and biodiesel was expressed as the ratio of the chemical energy provided by ammonia to the total chemical energy of ammonia and biodiesel. Hereafter, this quantity is denoted by the abbreviation AES (ammonia energy share).

Figure 16 shows the transmission efficiency characteristics in range of variations in internal combustion engine speed for all 6 tractor gear ratios. Figure 17, on the other hand, shows the power loss occurring in the transmission system as a function of the ratio used and the speed of the internal combustion engine, i.e. the speed at the entrance to the gearbox. Transmission efficiency was defined as the ratio of power at the wheels of the tractor to power at the crankshaft of the internal combustion engine.

The use of high gear ratios (G1 - G3) is associated with low efficiency in converting power from

the internal combustion engine shaft to the running wheels of the prototype tractor. Therefore, in order to maximise the efficiency of converting the chemical energy of the fuel to the work of the tractor's road wheels, the operating time of the tractor in gears G1 to G3 should be limited.

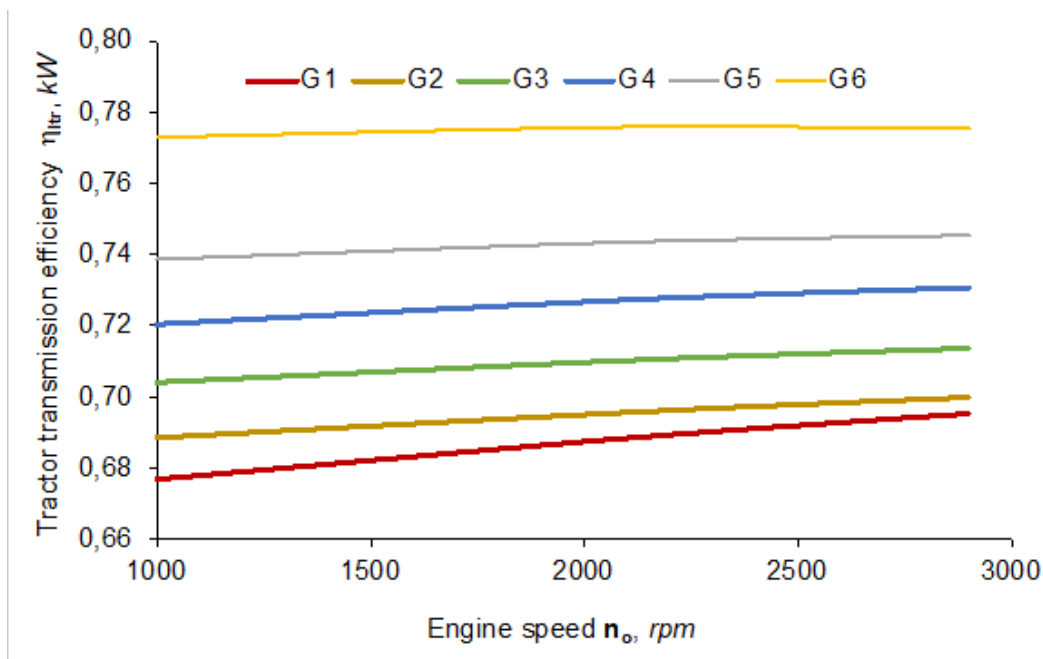


Figure 16: Tractor transmission system efficiency

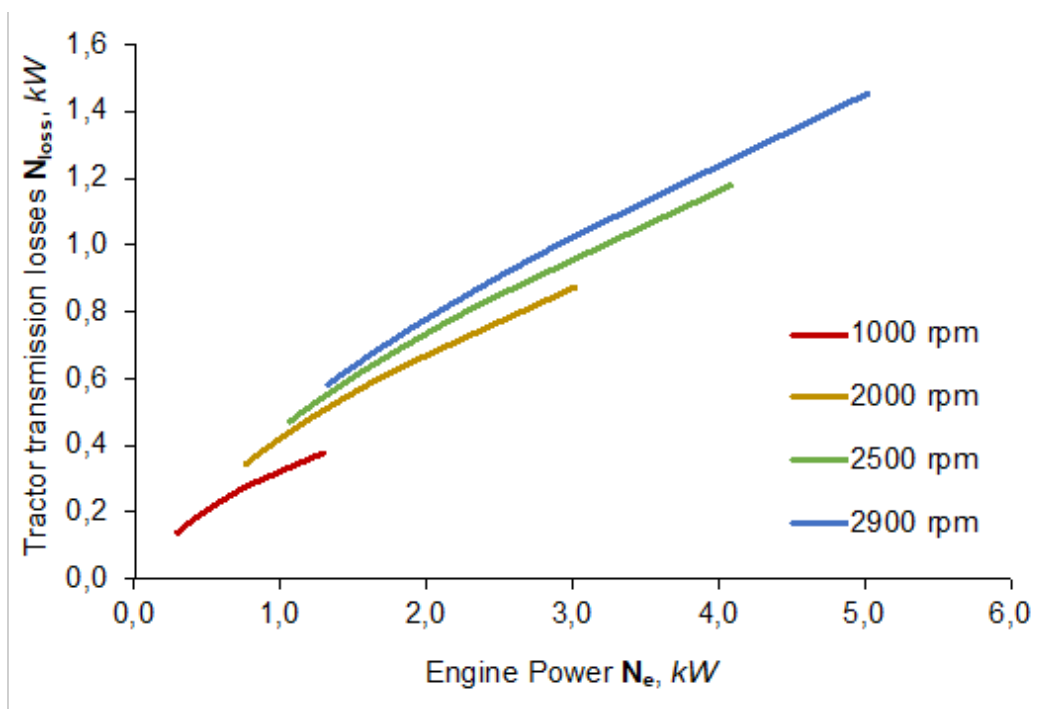


Figure 17: Tractor transmission system power losses

Figures 18 to 23 present the traction characteristics of the tractor for each gear ratio. The AES values result from the technical limitations of the injector and the ammonia combustion characteristics of the compression-ignition engine.

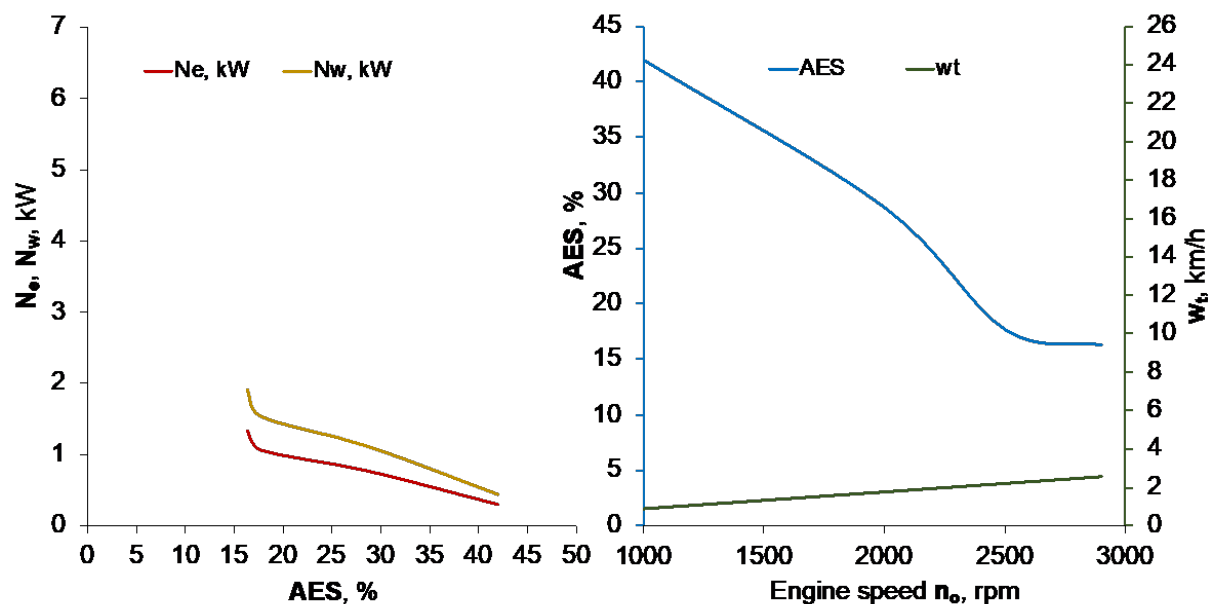


Figure 18: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G1.

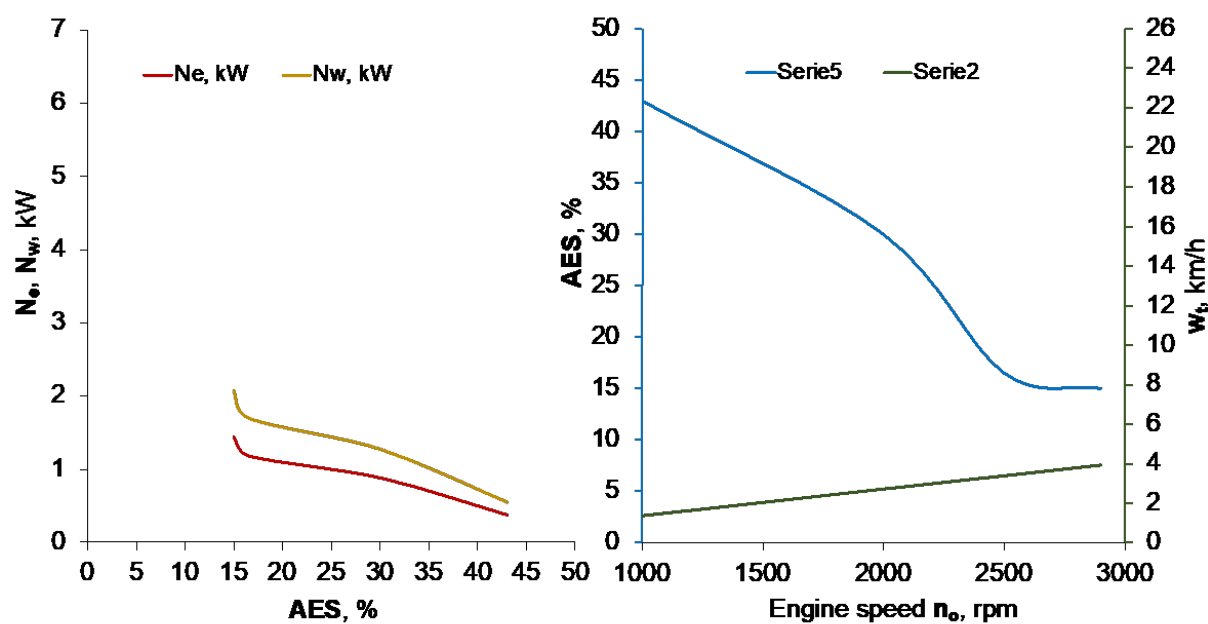


Figure 19: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G2

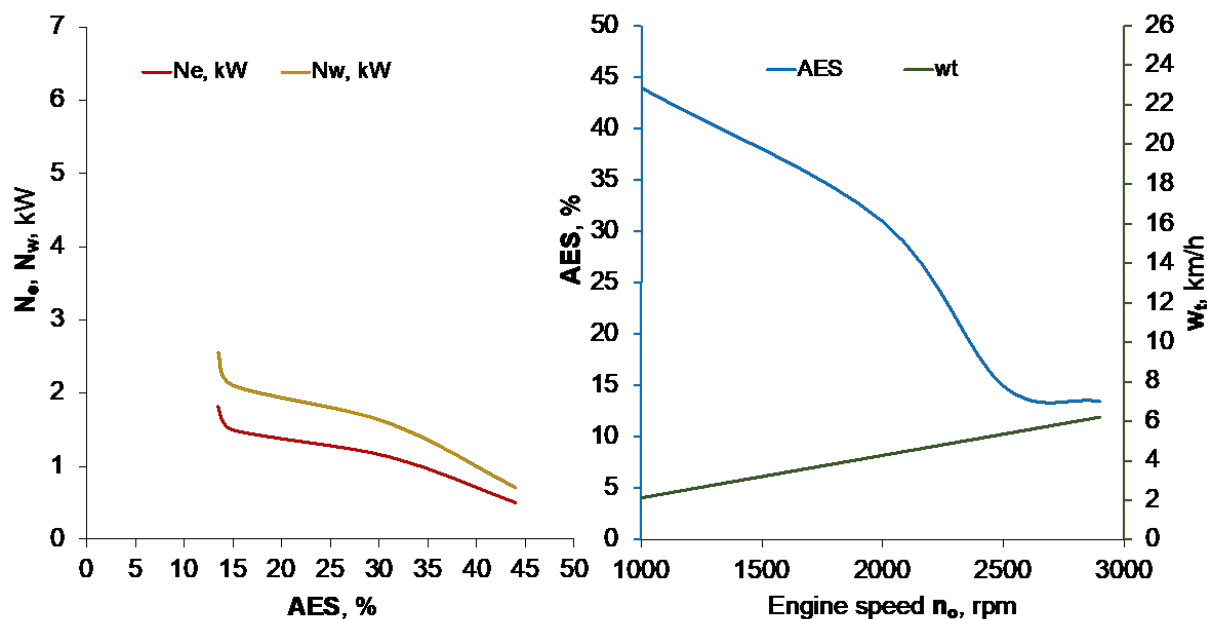


Figure 20: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G3

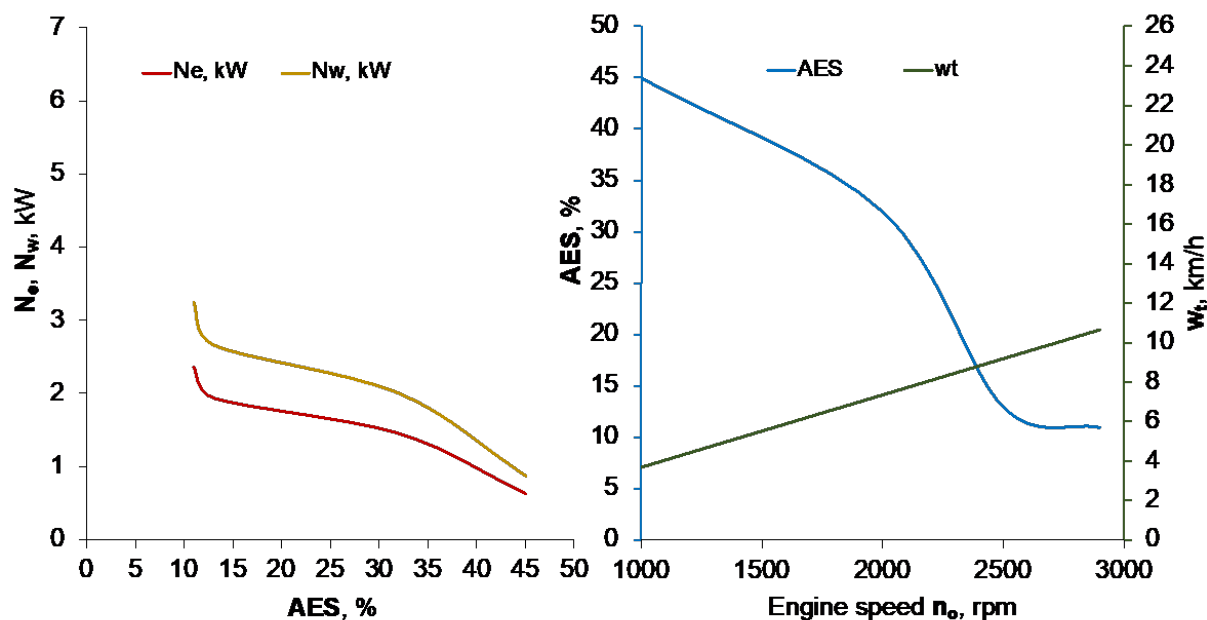


Figure 21: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G4

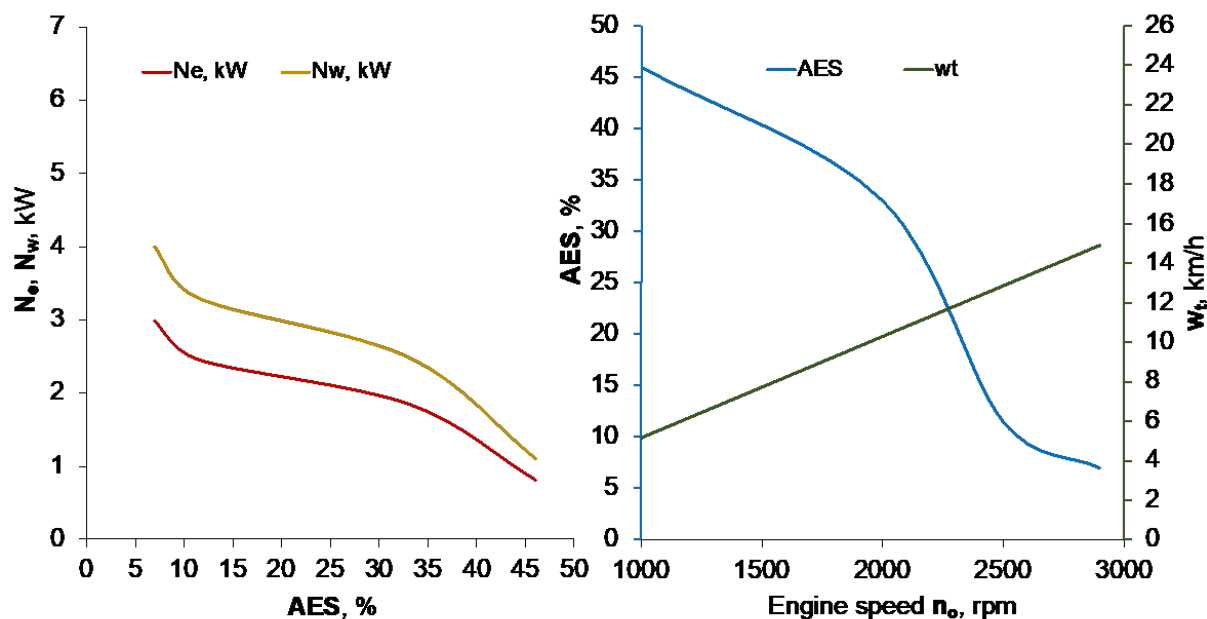


Figure 22: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G5

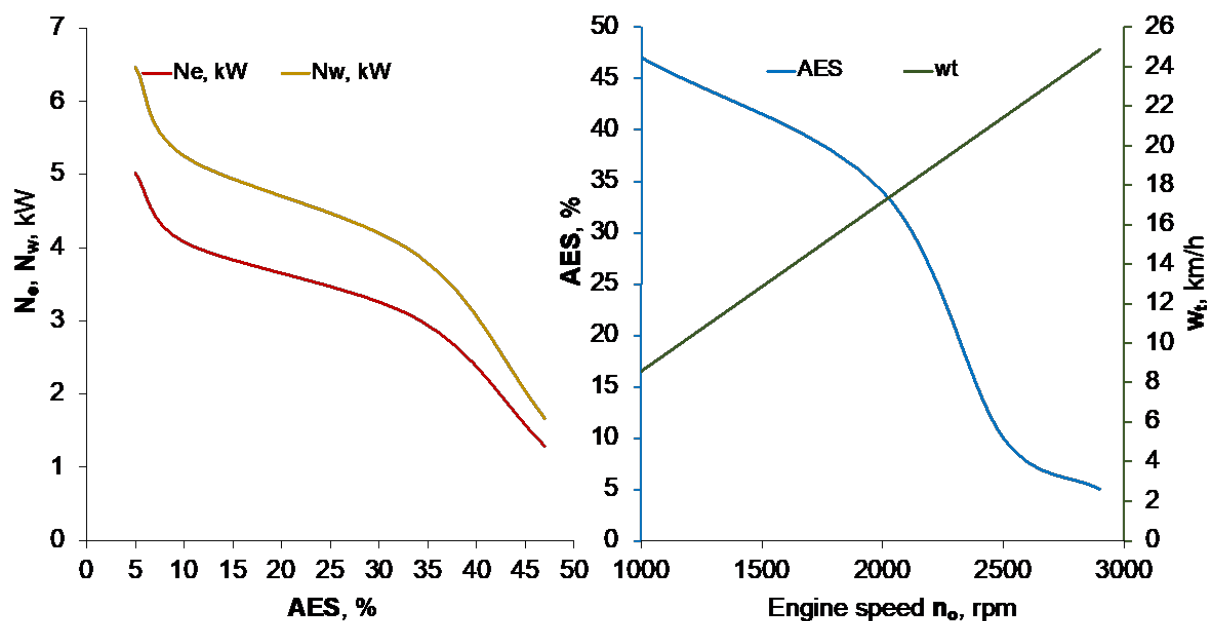


Figure 23: Engine shaft (N_e) and tractor wheel (N_w) power vs ammonia energy share AES – left, AES and tractor speed vs engine speed – right. Gear G6

The maximum energy substitution of biodiesel with ammonia expressed as AES was 47% and was achieved for an engine speed of 1000 rpm. A limitation of the use of higher ammonia doses was the high content of ammonia in the flue gas, i.e. exceeding 5,000 ppm (molar fraction in the wet flue

gas). Another limiting factor in the amount of ammonia burned was the efficiency of the injectors. Performance limitations are particularly evident at engine speeds above 2000 rpm. Due to the lack of dedicated injectors on the market for direct injection of ammonia into the engine cylinder, the use of a GDI injector is one of the technical limitations of the CI engine ammonia supply system developed in this project. Another limitation to the possibility of using high AES values when operating the engine at speeds above 2000 rpm is the low speed of flame propagation during ammonia combustion. Despite the use of different injection strategies for both ammonia and biodiesel pilot dose, achieving higher engine speed and power output values was associated with high ammonia content in the exhaust gas.

4 Determination of the emission factors of an agricultural tractor in a working field covering the operating conditions of the actual tractor

In the course of testing the traction characteristics of the tractor, the composition of the exhaust gases at the tailpipe outlet was measured. Figures 24 to 27 showcase the outcomes pertaining to specific emissions of CO_2 , CO , N_2O , and NO . These emissions have been calculated for the power generated at the crankshaft of the combustion engine. The calculations were carried out for different gear ratios responsible for transmitting power to the tractor wheels within the spectrum of AES (Ammonia Energy Share) variations.

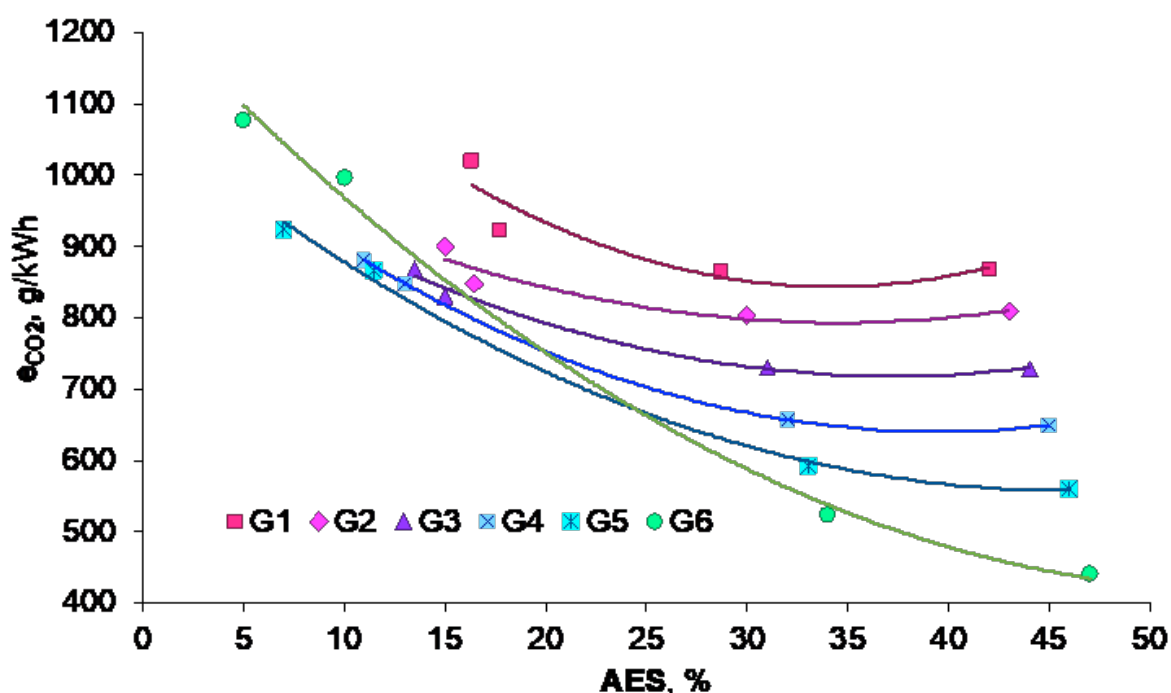


Figure 24: Specific emission of CO_2 vs AES for different tractor gear ratios

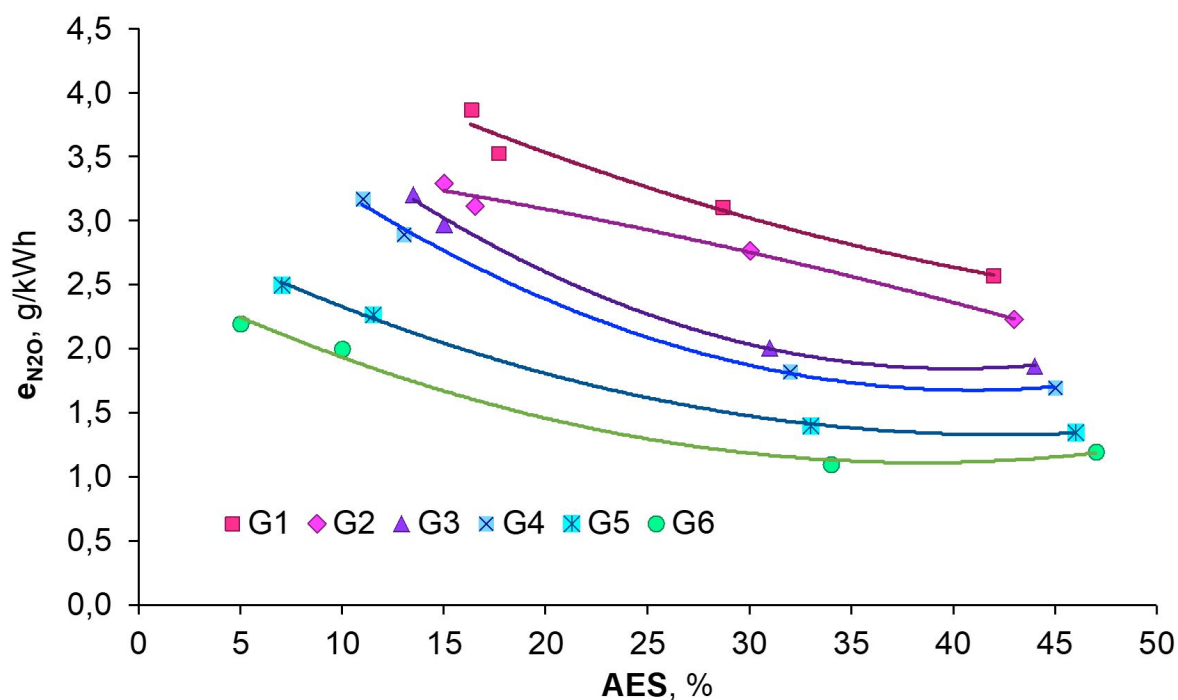


Figure 25: Specific emission of CO vs AES for for different tractor gear ratios

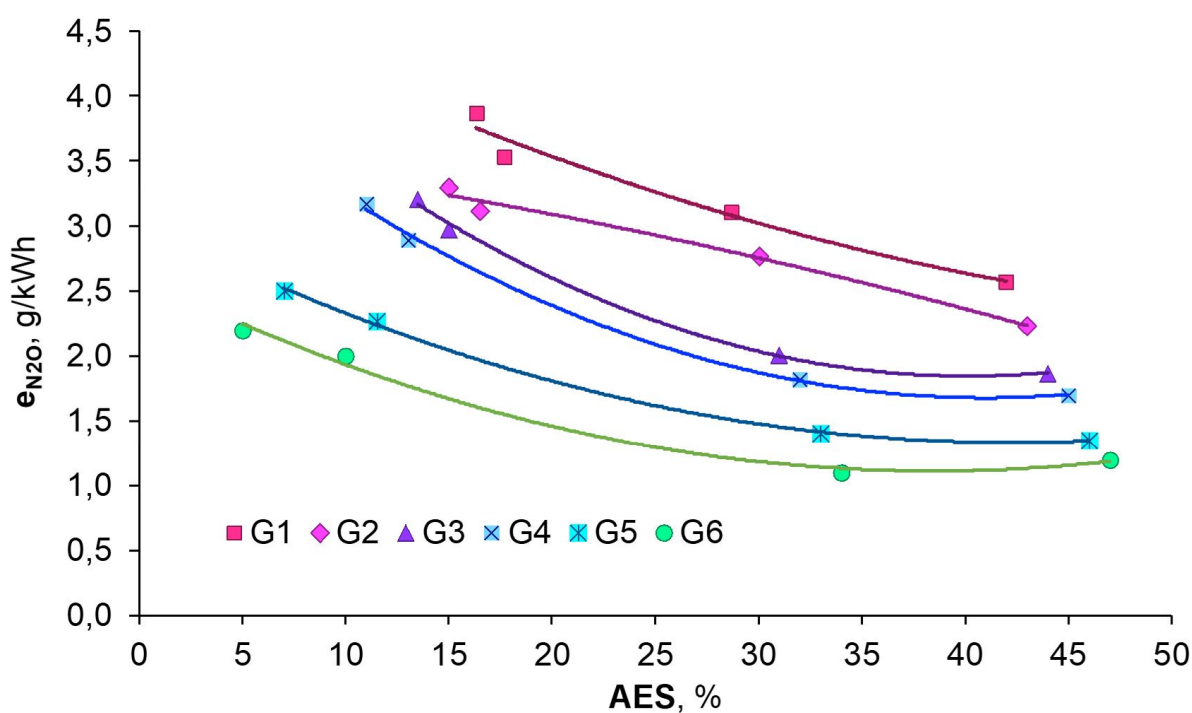


Figure 26: Specific emission of N₂O vs AES for different tractor gear ratios

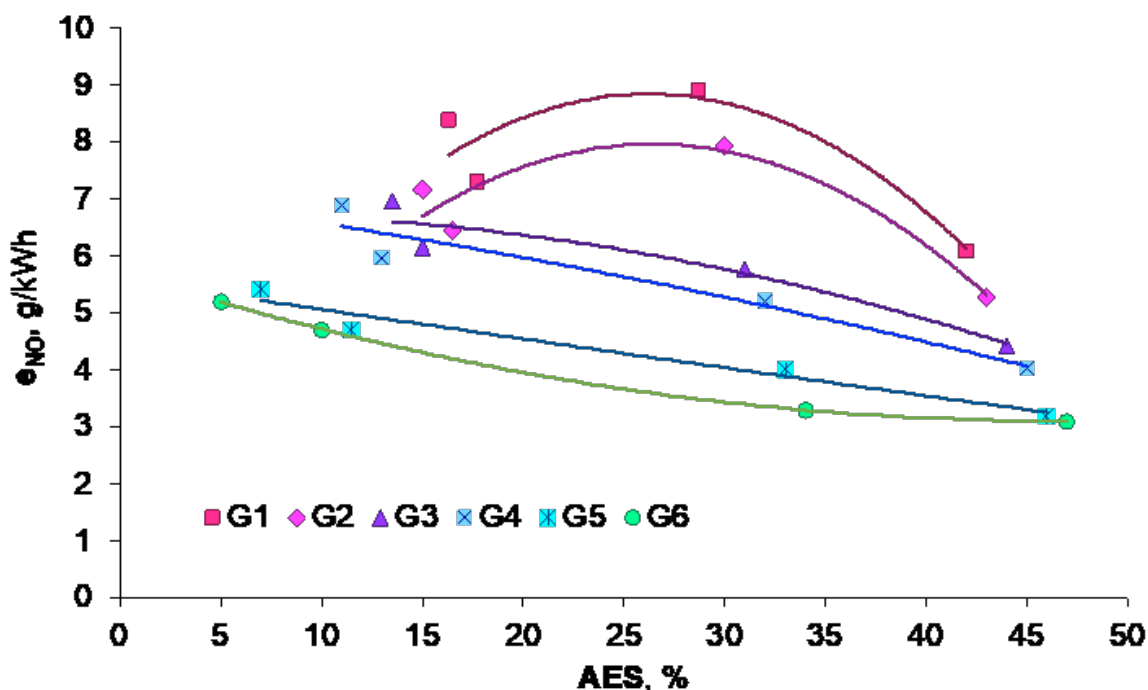


Figure 27: Specific emission of NO vs AES for different tractor gear ratios

The most favorable specific CO_2 emissions result from utilizing the tractor in the gear range from G3 to G6, along with powering the engine with an AES exceeding 20%. This can be attributed primarily to the higher substitution of biodiesel with ammonia and, in part, to the utilization of the engine in a field of operation characterized by enhanced energy efficiency. The specific emissions of NO and N_2O also exhibit the most favorable values during tractor operation when utilizing gear ratios ranging from G3 to G6. The reduction in emissions of these substances as AES increases can be attributed primarily to the fact that these engine operating points correspond to relatively lower loads, resulting in a correspondingly lower average temperature within the cylinder. On the other hand, the occurrence of high CO emissions in the gear ratio range discussed can be attributed to unfavorable thermal conditions associated with low engine load. However, the increased CO emissions observed for G1 and G2 gears in the lower "AES" range can be attributed to the fact that a significant portion of the fuel's chemical energy is released by burning higher doses of biodiesel.