Development of the methodology of exhaust emissions measurement under RDE (Real Driving Emissions) conditions for non-road mobile machinery (NRMM) vehicles

J Merkisz¹, P Lijewski¹, P Fuc¹, M Siedlecki¹ and A Ziolkowski¹

¹Poznan University of Technology, Institute of Combustion Engines and Transport, Piotrowo 3, 60-965 Poznan
E-mail: maciej.s.siedlecki@doctorate.put.poznan.pl

The paper analyzes the exhaust emissions from farm vehicles based on research performed under field conditions (RDE) according to the NTE procedure. This analysis has shown that it is hard to meet the NTE requirements under field conditions (engine operation in the NTE zone for at least 30 seconds). Due to a very high variability of the engine conditions, the share of a valid number of NTE windows in the field test is small throughout the entire test. For this reason, a modification of the measurement and exhaust emissions calculation methodology has been proposed for farm vehicles of the NRMM group. A test has been developed composed of the following phases: trip to the operation site (paved roads) and field operations (including u-turns and maneuvering). The range of the operation time share in individual test phases has been determined. A change in the method of calculating the real exhaust emissions has also been implemented in relation to the NTE procedure.

1. Introduction
In the beginning of the twenty-first century, one of the major challenges of humanity is to reduce the negative effects of the development of civilization. An undesirable aspect of this development is the degradation of the environment, and for this reason measures to reduce this degradation are increasingly gaining in importance. Undoubtedly, widely understood transport has a large negative impact on the environment, namely transport powered by internal combustion engines. For this reason, the development of modern internal combustion engines is based around ecological issues. Engines for off-road applications (non-road) represent a large share of engines in addition to those used in road vehicles. Engines used in vehicles for non-road applications NRMM (Non-Road Mobile Machinery) belong in this group. Engines of these vehicles are characterized by specific working conditions among all non-road engines that do not allow for them to be classified as traction engines. The group of NRMM vehicles includes machinery, tractors and agricultural machinery, and special purpose machines. The main problem for NRMM vehicles is the emission of PM (Particulate Matter) and NOx (Nitric Oxides). The scale of the problem can be illustrated by the situation in Germany, where the share of PM emissions coming from the engines of off-road application vehicles remained unchanged for years, at around 50% [1].
An important aspect of reducing emission of toxic fumes is the methodology of research. Currently, research on emission of toxic compounds from NRMM vehicles is performed mainly in the laboratory. These measurements apply only to the engine itself, and not the entire vehicle - and therefore the results of such studies do not give full information about emissions and fuel consumption during real operation. For the ecological assessment of the vehicles tests under real operating conditions are the most important, because only in this way it is possible to obtain complete information about the actual emission of harmful exhaust has components. The disadvantage of such research is the high cost of the measuring equipment and the need to adapt the vehicle for the needs of the test. However, it generates reliable results that are impossible to obtain in a laboratory, during tests on an engine or chassis dynamometer [2]. Currently, the measurements of emissions are carried out under real operating conditions of vehicles using mobile devices such PEMS (Portable Emission Measurement System).

2. Legal conditions for the type approval of NRMM vehicles with regard to emissions

Guidelines for testing emission of harmful exhaust compounds from NRMM vehicles are contained in the 97/68/EC Directive. The directive developed later [2] introduced changes and additions, which were mainly due to technical progress in the construction of engines and the increasing degree of standardization of regulations on a global scale. Hence, the introduced provisions were often common agreements between the European Commission and the US Environmental Protection Agency [3]. The desire to harmonize the regulations is an action desirable not only in Europe but throughout the whole world. The last directive on emissions of toxic gases from motor NRMM vehicles was published in December 2012 [4]. The Directive pays particular attention to the problem of reducing the NO\textsubscript{x} emissions. This is connected with the necessity of using an SCR. An important part of the directive, which should be noted, is the statement about the need to include the regulations from the Directive 595/2009/EC relating to the engines of road HDVs in the 97/68/EC Directive. This provision appeared with the introduction of the procedures for type approval testing under real operating conditions. Therefore, it is expected that the engines of NRMM vehicles solutions will be accepted that have been well established already in the tests for HDV engines.

Currently in force worldwide approval static test for non-vehicle applications of combustion engines is the emission test ISO 8178 (Figure 1) developed by the ISO (International Standard Organization) [4]. This is an 11-phase test performed on an engine dynamometer. Based on the test results the average emissions of the individual components of emissions are determined. The characteristic factors of the share in each phase of the test are selected depending on the intended application of the test engine. For NRMM vehicles a basic static test is an ISO 8178-C1.

![Figure 1. Schematic of an 11-phase ISO 8178 test](image_url)

Since coming into effect of the Stage III limit the emission measurements for NRMM vehicles are also carried out in the dynamic test NRTC (Non-Road Transient Cycle, Figure 2). In addition, the name of
the ISO 8178 test changed to NRSC (Non-Road Stationary Cycle). NRTC test was developed jointly by the European and American legislation. The NRTC test is performed twice on each tested engine: once for cold and once for hot start. The final result is a weighted average, with the share of 0.1 for the test with a cold engine start (in the United States - 0.05) [5]. In the NRTC test the speed of the engine crankshaft is determined according to:

\[
s = \frac{\% \ s_{nor} (s_{ref} - s_{idle})}{100} + s_{idle}
\]

(1)

where: 
- \(s_{nor}\) – normalized engine speed,
- \(s_{idle}\) – engine speed at idle
- \(s_{ref}\) – reference speed calculated with the formula:

\[
s_{ref} = s_{50} + 0.95(s_{70} - s_{50})
\]

(2)

where: 
- \(s_{50}\) – minimum engine speed, at which the engine reaches 50% of its nominal power,
- \(s_{70}\) – maximum engine speed, at which the engine reaches 70% of its nominal power.

The engine torque in the NRTC test is determined according to the relationship:

\[
T_o = \frac{\% \ T_{o,nor} \cdot T_{o,max}}{100}
\]

(3)

where: 
- \(T_{o,nor}\) – normalized engine torque,
- \(T_{o,max}\) – maximum engine torque.

These tests, however, do not reflect actual operating conditions of many machines and equipment belonging to the NRMM group. For this reason, an attempt was made to develop procedures for measuring emissions of toxic compounds in real operating conditions, the RDE (Real Driving Emission), using mobile analyzers of exhaust gases belonging to the PEMS category (Portable Emission Measurement System). The European legislation assumes that the procedures developed to test vehicles of HDV category (Heavy Duty Vehicles) laid down by Directive UE582/2011 will be adapted to test NRMM vehicles. In the case of US regulations it is assumed that the research in actual operating conditions will be performed in the NTE test (Not-To-Exceed), the same test that applies for
heavy duty vehicles. And so starting from 2011 an NTE test is performed for NRMM vehicles with an
eengine power greater than 130 kW, and from 2012 for engines with power of 56-130 kW.
The US Environmental Protection Agency has also introduced regulations limiting emissions during
the operation of motor vehicles with off-road applications. Under these provisions, NTE test (Not-To-
Exceed) were introduced along with emission limits set in this test, as an additional tool to control the
emission of toxic exhaust compounds (NTE is also the name of the norms for this testing procedure)
[5]. Measurements in this test are performed under real operating conditions of engines. The NTE was
originally introduced for engines of HDV road vehicles, and since 2011 it also applies to motor
vehicles with off-road applications with power greater than 130 kW, from 2012 for engines with
power between 56-130 kW, and from 2013 for engines with less than 56 kW of power. It should be
noted, however, that the NTE test was adopted for the NRMM vehicles in the same form as it exists
for HDVs.
Measurements in the NTE test are not associated with a particular drive cycle of the vehicle or the
operating points of the engine, there is no specified test run and time constraints (Figure 3). These
studies cover a range of engine operating conditions which exists within the NTE control area (the
NTE zone), including steady state and in transient conditions. Emissions of toxic compounds are
averaged with the engine cycle lasting a minimum of 30 seconds, called the measuring window (30
sec window). In the NTE test control an area bounded by the values of load and speed of the
crankshaft was established on the engine operation map:
- the minimum speed of the engine crankshaft A is set analogous to the speed designated in the
  ESC test (European Stationary Cycle, likewise with speed B),
- engine load equal to or greater than 30% of the maximum engine torque,
- all operating points for which the engine reaches less than 30% of the maximum power are
  excluded from the NTE area,
- the engine manufacturer may request that speeds and loads for which the specific fuel
  consumption is greater than 5% of the minimum be excluded from the NTE area when they can expect
  that the engine will not work when operating in those areas. This does not apply to engines
  cooperating with the automatic transmission with a certain number of gear ratios and vehicles with
  manual transmission.

Figure 3. NTE test for engines of NRMM vehicles, a) – for engines with a maximum speed of 2400
rpm, b) – for engines with maximum speed of up to 2400 rpm [5].

In accordance with the requirements set by the EPA all NRMM engines of vehicles that meet the Tier
4 norms, they must also meet the requirements of NTE. For engines of NRMM vehicles with power
greater than 130 kW, these provisions apply from 2011, for engines with power of 56-130 kW from
2012, while for engines of less than 56 kW from 2013. Limits on emission of toxic compounds in an
NTE test has been established as 1.25 of the permitted emissions of a given compound in Tier 4
norms. Only for engines that have NO_x emissions of less than 2.5 g/kWh and PM emissions of less
than 0.07 g/kWh the chosen multiplier is 1.5. The NTE rules apply for type approval tests as well as
for the entire lifespan of the engine [5].
3. Research methodology

The study used a John Deere farm tractor 6630. Technical data was given in Table 1. A picture of the vehicle with mounted test apparatus is shown in Figure 4.

| Name                        | John Deere 6630               |
|-----------------------------|-------------------------------|
| Number of cylinders / displacement | 6 cylinder inline / 6.8 dm³ |
| Maximum power               | 110 kW at 2100 rpm            |
| Curb weight                 | 5230 kg                       |
| Charging                    | VGT Turbocharger              |
| Cooling                     | Liquid with forced circulation|
| Injection system            | Common Rail                  |
| Number of valves            | 24                            |
| Emission norm               | Stage IIIB                    |

The authors used a portable exhaust emissions analyzer (SEMTECH DS by SENSORS, Figure 5) to measure the concentration of the exhaust components. The analyzer measures the concentration of the components and simultaneously measures the flow rate of the gas. The exhaust gas is introduced into the analyzer through a probe maintaining the temperature of 191°C. The PM is filtered out (compression ignition engines) and the exhaust gas is directed to the flame-ionizing detector (FID) where the concentration of HC is measured. The exhaust gas is then chilled to the temperature of 4°C and the measurement of the concentration of NOₓ (NDUV analyzer), CO, CO₂ (NDIR analyzer) and O₂ follows in the listed order. It is also possible to collect data from the vehicle diagnostic system. Aside from the exhaust emission values, signals from the on-board diagnostic system were recorded (engine speed, load, etc.) for the purpose of comparison. The lack of rules concerning the connectors and protocols of data transmission means that during the research of NRMM vehicles it is necessary to use the service diagnostic equipment to measure parameters of the engine.

Tractor sowing was performed on a rectangular field, located near Poznan. The route was characterized by a long, monotonous ride parallel to the sides of the field and U-turns (Figure 6). Before and after turning the tractor stopped and raised or lowered the cultivator.
A very important aspect when making measurements in the field is the terrain. In the first cycle of the research presented, in the middle of the field length, a significant change in altitude was recorded, which amounted to a maximum of 7 meters. This trough had a length of several meters and then returned to the normal level, which varied in the range of 80-82 m (Figure 7). Changing the height of the terrain affects the emissions of CO$_2$, which in the first part decreased and then increased. The engine operating points changed accordingly, stepping beyond the bounds of engine operating area for the NTE test.

![Figure 5. SEMTECH DS-analyzer and an exhaust gas mass flowmeter from SENSORS Inc.](image)

**Figure 5.** SEMTECH DS-analyzer and an exhaust gas mass flowmeter from SENSORS Inc.

![Figure 6. The route of the tractor during field work [developed based on: www.gpsvisualizer.com].](image)

**Figure 6.** The route of the tractor during field work [developed based on: www.gpsvisualizer.com].

![Figure 7. Changes in altitude and carbon dioxide emissions during field work in one measurement cycle.](image)

**Figure 7.** Changes in altitude and carbon dioxide emissions during field work in one measurement cycle.
4. The results of rde tests for nrmm vehicles

The performed research allowed to collect data on the performance of engines under real operating conditions. Particularly useful in the described analysis are: the rotational speed of the crankshaft and the engine torque. Electronic control and diagnostics systems used in modern NRMM vehicles provide some data and parameters on the operating conditions of the engine. This data is used for the needs of vehicle servicing. The type and amount of information that can be read depend on the manufacturer and also on the vehicle. These are individual solutions – each manufacturer selects the range of available service information according to their own criteria. Work is currently underway to standardize data exchange protocols, diagnostic connectors, as it has already been done for road vehicles. For the analyzes carried out for this article only some of the parameters relating to the working conditions of engines were relevant.

During the research the farm tractor was performing field work with a cultivator. Two measuring cycles were registered. In the first the tractor was performing light work of cultivation, representing a large group of works for seedbed preparation and cultivation performed in agriculture. The second measurement cycle concerned the passage of the tractor on asphalt roads from the farm to the farmland. In the first cycle the tractor engine worked in a narrow range of crankshaft speed and torque. The most commonly used operating range is 1700-1800 rpm and 200-500 Nm, it represented 68% of total work time (Figure 8). Significant shares were also for the speed range 1800-1900 rpm and a load of 200-400 Nm and the engine idle operation area 900-1100 rpm – these accounted for 11 and 7% of the time share respectively. In the field test cycle, a significant work time share of 6%, was the idle area or 900-1000 rpm.

![Figure 8. Engine time density characteristics of a tractor during field cycle](image)

During the drive on the road of the tractor almost the entire range of crankshaft speed and engine load has been used (Fig. 9). The resulting characteristics of the participation of speed and load of the tractor is similar to the characteristics of the engines of rail vehicles [6]. However, it is possible to distinguish two main operating areas that were most frequently used. The first is the engine speed range of 800-1300 rpm and load 0-210 Nm - its share in the cycle was 35% (1 in Fig. 9). The second is the engine speed range of 1300-1900 rpm and a load of 140-550 Nm. The share of this area was 57% (2 in Figure 9). During the drive on a road the work time share of load exceeding 75% of the maximum was very small. In addition, the large share of the engine idling time - 15%, and thus a share higher than during field work, should be noted.
Figure 9. Engine time density characteristics of a tractor during drive cycle.

Points of engine operation recorded during testing in actual operating conditions were compared to the NTE test. For the tractor area of the engine work in the first test cycle is only partially located in the area of the NTE test (Figure 10). Seven important NTE test windows were registered in it, which represents 25% of the time the engine operation. During the passage of the tractor on the road 48% of the work time share the engine worked in the area of the NTE test and recorded 17 major windows, with a total length of 1,015 s, which accounted for 22% of the total work time of the engine (Figure 11). This small part is the result of the frequent changes in speed and load of the engine. The required condition of maintaining constant operating parameters of the engine for 30 s under NTE test was difficult to meet.

Figure 10. Operating parameters in real operating conditions and the NTE test of a tractor engine (1 measuring cycle).
5. Assumptions of rde measurement methodology for agricultural vehicles

The RDE measurements in real operating conditions made using PEMS equipment for the tractor demonstrated that the NTE method to assess emissions is not representative of the conditions of the engines in operating agricultural vehicles. This was also confirmed by previous research done by the authors presented in publications [6, 7]. Based the information acquired, assumptions for research methodology have been developed, that enables accurate analysis of emissions during RDE measurements. The methodology consists of the following elements: establishing a test route, selection and preparation of the vehicle for testing, assembly and preparation of measurement equipment for the test, measurement procedure and calculation of emissions.

I. Selection of the test cycle

The test cycle should include performing measurements on both the roads and in the field. It should start in the place where the equipment was assembled. Subsequently, it should run along asphalt roads constituting the access to the place of work in the field, and return to the starting point. The share of this phase should not exceed 25% of the total engine work time. The main part of the measurement (75% of the time share) should be done in the field. The maximum slope of a field should not exceed 3%. The measurement should be at least 7200 seconds long. The length of the cultivated field should be enough to allow for the registration of parameters for at least 10 minutes, without the need for maneuvering. The vehicle must defeat four such episodes in one direction during the measurement. This is to increase the share of the work time of the internal combustion engine load characteristics – at constant speed of the engine crankshaft but variable torque. Making turns in the field causes a large variation in operating parameters of the engine, making it difficult for subsequent analysis using the NTE method.

II. Selection and preparation of the vehicle for testing.

The study should use agricultural vehicles which are equipped with internal combustion engines that enable communication between the measurement equipment PEMS and their diagnostic systems. This is very important because it enables the measurement or calculation of the torque generated by the engine during measurements. This is used to calculate the power output and the work that the engine generated during the measurements. In the case where the diagnostics network only enables the measurement of the parameter of Engine Load, which is the ratio of the current torque to the maximum torque at a given speed of the engine crankshaft, it is necessary to obtain the full power characteristics over the entire operating area of the engine from its manufacturer. The second parameter determining the choice of the vehicle should be the number of operating hours, which is a measure of the work time of the machine and is calculated as the difference between the time the work is completed and the it commenced. It is assumed that the agricultural vehicle must have a minimum of 500 operating hours total for it to be subjected to the RDE tests. When performing the measurements it should be equipped with proper cultivating machinery. The preparation of an agricultural vehicle for RDE testing should mainly concern the installation of measuring instruments. To place the PEMS apparatus on the vehicle, it is necessary to prepare an additional supporting structure mounted to the vehicle. It is associated with the large
dimensions and weight of the PEMS research equipment. The designed support should be characterized by appropriate endurance parameters, to not cause changes in the stability of the vehicle and to not adversely affect the safety of road traffic.

III. The assembly and preparation of the measurement equipment for the test

The PEMS apparatus should be installed in the vehicle in such a manner so as not to affect its stability and to not pose any threats when conducting measurements. Exhaust flow meter EFM should be tightly connected to the exhaust system of the internal combustion engine by means of a rigid, smooth tube with the lowest possible number of curving. It is important to remember that there must be a straight section of pipe with a minimum length equal to double its diameter before the EFM flowmeter. This is to reduce the pressure pulsations of exhaust gases. Due to the measurement including particulate matter the length of the pipe segment connecting the exhaust system with a flow meter should be as short as possible. The test apparatus must be powered from an external source mounted on the vehicle. This may be a battery, or a generator. It is not permissible to power the measuring equipment directly from the vehicle, because it would affect the work load of the engine. The vehicle must also be equipped with a GPS position sensor and a temperature, pressure and humidity sensors for the ambient air.

After the assembly of research equipment on the vehicle, its stability and the quality of the mounting should be checked – as during sudden longitudinal and transverse movements the measuring equipment should not move. Once checked it should be run in order to allow it to warm up and stabilize the working conditions. After stabilizing the temperature (device showing the ready signal or readiness signaled in the control software) it is suggested to wait 10-15 minutes to permanently stabilize the operating conditions of the apparatus.

IV. Procedure for measurement and calculation of emissions

Before the measurements the zeroing and calibration procedure of the research equipment must be performed. It should be carried out after the stabilization of the apparatus (including those suggested additional few minutes). But the wait time cannot exceed one hour. To do this, follow the instructions of the PEMS equipment. First, the airtightness of the heated conduits should be tested, both those for the measurement of gaseous compounds and particulate matter. Then, a zeroing of the device should be performed – there are two methods involving either zeroing with the use of ambient air or a calibrating gas (synthetic air, nitrogen). In the case of ambient air, zeroing procedure should take place in an area where there is no excess emission of toxic compounds. When calibrating with ambient air the equipment requires the control device to be zeroed at least once per hour in the course of the measurement, and in the case of using calibration gases the reference gas canister should be placed inside the vehicle and connected to the apparatus. Then the procedure is performed using a calibration gas mixture recommended by the manufacturer. The whole process should be recorded. After completion of the measurement a control calibration of the instrument should be performed according to the methodology described before. After completion of the zeroing and calibration of the instrument it is necessary to flush and reset the EFM flowmeter. Before the measurement of particulate matter a filter should be placed through which the diluted exhaust sample will flow. Filters should be conditioned prior to measurement, weighed, and stored and transported in a special instrument protecting against weather conditions. After finishing the measurements the filters should also be put back into it, and then weighed again. Measurements should be performed at ambient temperatures above -7°C. Before the measurement the engine of the vehicle should be started and given sufficient time for the temperature of the coolant to reach 70°C. This should not last longer than 5 minutes. If this time is exceeded the measurements should begin. During the warm-up of the apparatus it should not be provided the exhaust gas sample, neither dedicated to the gaseous compounds not the particulate matter measuring devices. After completion of the measurement, the engine of the vehicle should be turned off and only after that the process of control zeroing and calibration.

The calculation of pollutant emissions should begin with the designation of the area specified in the NTE method. Then the measuring windows should be designated and if they accounted for over 50% of the total work time the emissions can be calculated according to the guidelines of the NTE (presented in Chapter 2). If the required validity of the measuring windows is not satisfied the work which the engine
6. Conclusions
The analysis of emissions performed in this article is in accordance with the rules of the NTE procedure, performed on the basis of RDE measurements has shown that the NTE procedure under typical operating conditions of agricultural vehicles does not meet its target. For this purpose, it is necessary to modify or replace it with another. On the basis of the tests performed and previous experience the authors suggested research methodology, which takes into account:

a) the choice of test route,
b) selection and preparation of the vehicle for testing,
c) assembly and preparation of the measurement equipment for the test,
d) Procedure for measurement and calculation of emissions.

Especially important in this method is to determine a test cycle that takes into account operation on asphalt roads and work in the field. It was assumed that its duration must be at least 7,200 seconds and 75% of the operating time is to dedicated to the work in the field. The characteristics of the field was also defined – one passage on the field is to take 10 minutes without making turns. Four runs in each direction should be performed during the measurements. As a result, the share of valid measurement windows in the NTE method is expected to increase. If it does not exceed 50% of the work time then the engine work performed in the measurements should be determined. If it is larger than the work generated in the NRTC test the calculations should be carried out according to the initial proposal the European method dedicated for NRMM vehicles proposed by the European Commission.

References
[1] Commission Directive 2010/26/EU of 31 March 2010 amending Directive 97/68/EC of the European Parliament and of the Council on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery
[2] Chandan M Boopathi S John and Arun C 2014 System Strategy To Meet Tier4 Final Emission Regulations In a Locomotive Application For a Large Bore High Speed Diesel Engine Proc. ASME 2014 Internal Combustion Engine Division Fall Technical Conf. (USA, Columbus)
[3] Analysis of Diesel Emissions in the U.S.-Mexico Border Region 2007 report prepared by: Industrial Economics, Incorporated Cambridge and Ross & Associates Environmental Consulting, Ltd. prepared for: U.S. EPA Office of International Affairs
[4] Friedrich A 2008 Emission Legislation for Off-Highway Application in Germany. Proc. Int. CTI Forum Emission Reduction Systems for Off-highway Applications (Germany, Stuttgart)
[5] Worldwide Emissions Standards, Heavy Duty and Off-Highway Vehicles. Delphi brochure 2015/2016
[6] Lijewski P Merkisz J Fuc P Siedlecki M and Ziolkowski A 2015 The Measurement of Particulate Matter from Construction Machinery under Actual Operating Conditions SAE Technical Paper 2015-01-2810, 2015, doi:10.4271/2015-01-2810
[7] Lijewski P Merkisz J and Fuc P 2013 The Analysis of the Operating Conditions of Farm Machinery Engines in Regard to Exhaust Emissions Legislation. Applied Engineering in Agriculture, Vol. 29(4), 2013

Acknowledgments
The research was funded by the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju) – research project within the Applied Research Programme (contract No. PBS3/A6/26/2015)