

Real World Duty Cycle Development Method for Non-road Mobile Machinery (NRMM)

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ABSTRACT

Emission, fuel economy and productivity in non-road mobile machinery (NRMM) depend largely on drive cycles. Understanding drive cycles can provide the in-depth information and knowledge that help the system integrator better optimize the vehicle management system. Some non-road engine test cycles already exist nowadays. However, these cycles are mainly for engine emission regulation purpose, and not closely tied to real world applications. Therefore, from both industries and academia, it has been the common practice to instrument and retrofit a vehicle, assign a professional driver operate the retrofitted vehicle for real testing, and compare the results to the baseline vehicle under the similar operating conditions. Obviously this approach is time consuming and resource intensive. In this paper, we attempt to address this issue by introducing a method of constructing standard drive cycles from in-field operation data. The constructed drive cycle will affect design, analysis, optimization and testing of NRMM. Moreover, the standardization of such drive cycles will ease measurement of performance metrics across the industry.

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INTRODUCTION

Concerns about human health, climate change and energy crisis have stimulated the development of regulations for on road vehicles. With the better understanding of the impact for non-road mobile machinery (NRMM) - e.g., NRMM contributes to approximately 1.3 Quads(10^{15} BTU) /year for USA only [11] - the regulations for NRMM have been catching up very quickly and aggressively. Since 1997, USA and Europe have driven the ever-increasingly stringent emission regulations. With already tight limit for Tier 4 and Stage IV, European Commission is developing then next phase of NRMM regulation, Stage V, which will become mandatory in 2019/2020/2021.

Given a NRMM, a drive cycle is a motion profile which would represent a typical real world operation. Once a new solution is introduced, the machinery OEMs and the subsystem suppliers very often want to verify the performance improvement. They rely heavily on professional operators since until now, there have been limited standardized duty cycles defined for NRMM areas except for a few engine emission testing cycles. In Both USA and Europe, ISO 8178-C is defined for engines operated under intermittent speed, ISO 8178-D under constant speed, and NRTC for engine transient testing. However, ISO 8178 does not adequately represent the actual emission produced by NRMM during day-to-day operations [10].

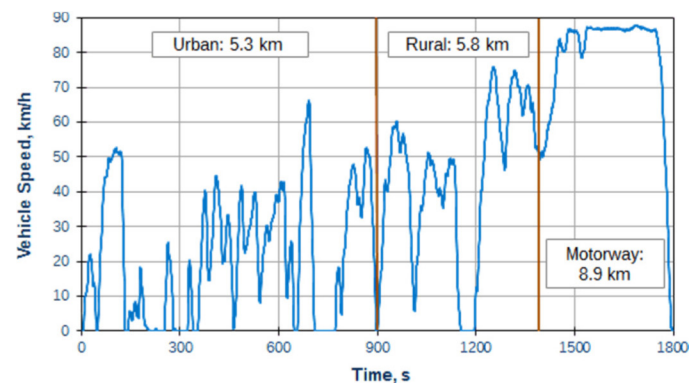


Figure 1. world harmonized vehicle cycle (WHVC) [12]

Therefore there will be the big gap between meeting the predefined - often simplified - test cycle and understanding the meaningful and realistic impact in real applications. In order to overcome such gap, more mature development has occurred in drive cycle standardization for automobiles and trucks. There are two types of methods of constructing on-highway vehicle drive cycle [1,9]. One is referred as polygonal where acceleration, deceleration and speed are all constant, like NEDC. The other is derived from real world duty cycles. The real world cycles are more dynamic and closer to the actual operation, thus being preferred. The primary category of drive cycles

is legislative related due to exhaust emission specification imposed by governments for cars and trucks. The most important regions include FTP-75 used in USA, NEDC used in Europe, and JC08 used in Japan. Standardized drive cycle development extends to other geographical regions such as Endinburgh, Hongkong, Athens, India and Thailand [2,3, 4]. Recently, there is a task force under UN ECE WP29 to develop worldwide harmonized cycles that will be transposed into regional regulations. It is dedicated to collecting and analyzing in-use data from different regions of the world, creating the worldwide unified database, and deriving harmonized cycles from this database [8]. During the testing, a chassis dynamometer will be used to track the speed profiles for urban, rural, and motorway for 20 min. the weighting applied for each the three segments can be varied between 0 to 1 to reflect different classes of vehicles. The profile of a world harmonized vehicle cycle (WHVC) can be seen in [Figure 1](#) [12].

Is it possible to adapt a similar drive cycle construction technique for NRMM? It is certainly value added since it would be closer the real world duty cycles, and therefore easier to conduct truly comparative performance scenarios for different systems. However, there are several challenges:

1. First, unlike the on-highway version-where you need to construct one cycle to represent real-world scenarios where a vehicle operates in urban or rural-off-highway cycles typically include much more discrete operation modes, thus being more challenging to form a single cycle.
2. Secondly, when it comes to each discrete mode (like trenching), the variation of physical variables is quite significant from one period to another. A number of factors, like human feel, dirt density, temperature, cause the variation. Determining the best way to find an 'average' profile is more difficult.
3. Thirdly, the level of complexity that need to considered in NRMM is much higher. While on highway vehicle drive cycles deal only with the speed and acceleration of the vehicle, NRMMs have much more degree of freedom (the number of actuators). In addition, the way to represent each degree of freedom is multi-dimensional including pressures, flow rates, temperatures, force, displacement, etc. Furthermore, we have to consider how to test them in a dyno even should a duty cycle be agreed.

In this paper, an approach of NRMM standard duty cycle development is proposed to address these challenges. First of all, a composite duty cycle is defined for various NRMM vehicle types by including the appropriate work modes to address Challenge 1. Then we will discuss the robust duty cycle development strategy from real world data to overcome challenge 2. Finally, in order to address Challenge 3, three different level of duty cycles have been proposed to compromise the complexity of multiple signals and the feasibility of test procedure implementation.

DEFINE COMPOSITE DUTY CYCLES FOR VARIOUS NRMM VEHICLE TYPES

Let's start from on-road vehicle world humanized test cycle as a reference. Recall in WHVC in [Figure 1](#), all vehicle will include working mode of "urban", "rural" and "motorway". However, different classes of vehicles will be specified by various weighting function to three pre-specified segments, namely 'urban', 'rural', or 'motorway'.

We would like to take the similar strategy for NRMM. Of course, the scenarios will be much more complex here. First of all, the number of the types of NRMM is significantly more than on-road counter-parts. Second, unlike only three segments in On-Road vehicles, the work modes for each type of vehicles will be very different.

Obviously, in order to get started, we need to build a master matrix to link the vehicle type to the working mode first. A simple template of such thought process can be in seen in [Table 1](#).

Table 1. Template of Master Matrix that link NRMM vehicle types to discrete work mode

Work mode ID	Work Mode Description	NRMM Types			
		Wheel loader	Excavator	Backhoe Loader	
1	Trench		X	X	
2	Truck loading		X	X	
3	Back fill		X	X	
4	On road driving	X		X	
5	Short Y cycle	X		X	
6	Long Y cycle	X		X	
...	...				

The work mode can be defined in the level so that it is a work pattern that can be found in more than one types of vehicles. On the one hand, the work mode cannot be too general. For instance In [7], the duty cycle defined for bull dozer is clearing land, which is very broad and hard to qualify. On the other hand, the work mode should not be defined too specific - the number of work mode would increase exponentially. For instance, for a "Y cycle" work mode, the wheel loader will go through bucket filling, leaving bank, reverse, toward the load receiver, bucket emptying, leaving load receiver, to the bank, and retardation at bank. These detailed procedure should be included in "Y cycle" as one work mode. They should NOT be extracted separately as many work modes to avoid proliferation.

Some duty cycles are shared by different vehicle types. For instance, trenching is common operation for both excavator and back hoe loader.

A harmonized duty cycle of a type of NRMM vehicle is then constructed in classification of all its representative work modes, namely :

$$D_{vehicle(i)} = \sum_{k=1}^n w_{i,k} D_k$$

in which

- $D_{vehicle(i)}$ is the overall composite duty cycle for the i -th type of vehicle. For example, in Table 1, vehicle(1):=“wheel loader”, vehicle(2):=“excavator”, vehicle(3):=backhoe loader, etc.
- D_k the duty cycle for k -th work mode,
- $W_{i,k}$ the weight function of the k -th work mode for i -th vehicle type. Given i , Obviously $\sum_{k=1}^n w_{i,k} = 1$.
- n is the total number of work modes for a exhaustive list in Table 1 after its completion.

In a similar manner to world harmonized vehicle cycle, $W_{i,k}$ can be assigned to different values for different types of NRMM vehicles, with additional fine tuning depending on vehicle classification, regional variation, and other parameters..

ROBUST DUTY CYCLE DEVELOPMENT FROM REAL WORLD DATA

Instead of the simplified profile, it would be very valuable to retrieve the duty cycle from real world data. As aforementioned, one big challenge is how to retrieve an average profile from the real word duty cycle that typically vary drastically. This section describes the strategy for the drive cycle formation for each discrete operation mode D_k . Similar to on-highway vehicle practice, we focus on using collected data as a baseline to define formation strategy. The strategy can be divided into the five major steps: identification of repeating procedure, cycle isolation, cycle resampling, outlier elimination and cycle connection.

Most of NRMM engine deliver power to non-road environment via hydraulic system, as least partially. For the hydraulic application, the assumption is that only hydraulic-related data are available. Without the loss of generality, the data available to understand the duty cycle include hydraulic actuator (cylinder or motor) position, pressures on each side (head side and rod side) and the pilot pressure signal generated from an user sending to a directional control valve. Data collection and assurance procedure will not be discussed in this paper.

1. Identification of Repeating Procedure

Once data is collected, the first step for generation of drive cycles is to identify repeating procedures in the raw data. NRMM operate for repetitive procedures, referred to henceforth as duty cycles. These duty cycles consist of multiple individual cycles. The drive cycle that we seek to generate will be a representative duty cycle for that operation. Through the identification of repeating procedures in raw data, we recognize the physical significance of duty cycles and individual cycles.

We consider the trenching operation of the backhoe loader as an example. A trenching operation consists of digging a rectangular ditch with certain length, breadth and depth. At certain position along the trench length, say x , the backhoe loader digs a ditch of the required depth and width and as much length as allowed by bucket reach. The total length of the trench is greater than the total reach of the backhoe loader's bucket. Hence, after the digging operation is complete, the backhoe loader moves forward along the trench length to a new position $x + \Delta x$, in which Δx is the incremental change of the vehicle position, and repeats the digging operation. Thus, the repeating procedure is the digging operation that the backhoe carries out at every position along the trench length. This operation constitutes a single duty cycle. One trenching duty cycle comprises the sequence of operations starting from when the backhoe loader starts operating at x until it moves to $x + \Delta x$ along the trench length. The trenching operation comprises multiple duty cycles since duty cycles are repeated along the length of the trench.

Moreover, one discrete mode of trenching, $D_{trenching}$ can occur in conjunction with other discrete modes. This is because the backhoe loader at a certain position x , will have to repeatedly remove the ground material and dump it to the side. We have to make sure to have enough granularity to separate different discrete modes.

The repeating procedure is clearly seen in the data for backhoe loader trenching operation as shown in Figure 2.

2. Cycle Isolation

The step following the identification of a repeating procedure is cycle isolation. The primary motivation for this step is to obtain individual and duty cycle start times (isolation data). There are three sub-steps under this category: Identification of base variable, isolation of individual cycles and isolation of duty cycles.

Identification of Base Variable

The base variable is the variable on which the isolation of the raw data into individual cycles and duty cycles is based. Thus, the base variable should have physical significance relating it to duty cycles and individual cycles. A certain variable is chosen as a base variable if it demonstrates sufficiently cyclic and noise free behavior which can be easily related to duty cycles and individual cycles.

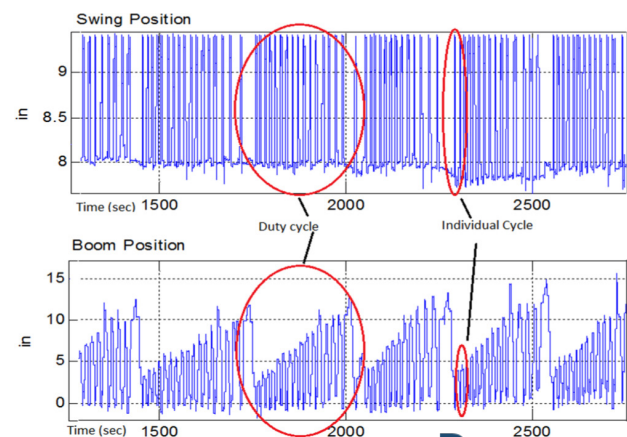


Figure 2. Backhoe loader swing and boom positions illustrating individual cycles and duty cycles