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Derivation of a Representative Engine Duty Cycle from On-Road Heavy-Duty Vehicle Driving Data

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Abstract

The heavy-duty vehicle fleet involved in delivering water and sand makes noticeable issues of exhaust emissions and fuel consumption in the process of shale gas development. To examine the possibility of converting these heavy-duty diesel engines to run on natural gas-diesel dual-fuel, a transient engine duty cycle representing the real-world engine working conditions is necessary. In this paper, a methodology is proposed, and a target engine duty cycle comprising of 2231 seconds is developed from on-road data collected from 11 on-road sand and water hauling trucks. The similarity of inherent characteristics of the developed cycle and the base trip observed is evidenced by the 2.05% error of standard deviation and average values for normalized engine speed and engine torque. Our results show that the proposed approach is expected to produce a representative cycle of in-use heavy-duty engine behavior.

Keywords

Engine Duty Cycles, On-Road Heavy-Duty Vehicles, Shale Gas Extraction

1. Introduction

In the process of shale gas development, heavy-duty diesel engines are extensively involved in material transport by over-the-road trucks, drilling rigs, hydraulic fracturing engines and other applications. Diesel fuel consumption is one of the largest costs in shale gas development, due to these prime-movers. The exhaust emissions from these conventional diesel engines can lead to negative environmental and health effects. Cost savings can be realized by converting these engines to run in natural gas-diesel dual-fuel operation. In order to measure the emissions from diesel and dual fuel engines, laboratory testing is performed on an engine dynamometer over a defined test schedule. Engine duty cycles determine the experimental results of any dynamometer test. However, an engine duty cycle representative of the real-world working condition of these engines is not defined, and standard certification cycles may not be representative of these conditions. Of the prime movers used in shale gas development, the working conditions of trucks associated with water and sand delivery are the most complex, due to the variable speed and load of these over-the-road engines. The objective of this contribution is to establish an engine duty cycle to represent the real-world working conditions of engines in trucks based on the on-road data collected.

To evaluate the fuel economy and exhaust emissions, a variety of vehicle chassis and engine duty cycles are used. Standard cycles are widely applied in chassis dynamometer and engine bench test by authorities, manufacturers, and fleet owners for engine and vehicle emissions certification. For light-duty vehicles in the United States (US), the commonly used standard vehicle drive cycles consist of the FTP72, FTP75, SFTP US06, SFTP SC03 and HWFET [1]. For heavy-duty vehicles in the US, instead of chassis dynamometer testing, only engine dynamometer testing over the Transient Heavy Duty Engine FTP cycle is required by federal regulations. Standard cycles for chassis or engine dynamometers offer a way to compare performance between different vehicles, however, they don't necessarily represent the behavior of all real-world operation [2]. Therefore, investigations are devoted to create representative driving cycles indicative of real world vehicle operation for specific traffic conditions in a particular area. For instance, a driving cycle was developed to estimate vehicular driving patterns in the Slovenian city of Celje and was compared with the driving cycles of other cities in Europe by Kneza *et al.* [3]. Also, different methods are studied to develop various driving cycles for a several cities in Asia [4] [5] [6] [7].

Unlike drive cycle development, there is limited literature published on engine duty cycle development based on real world operating conditions. As part of a regulatory program for the US Environmental Protection Agency (EPA) conducted to developed cycles for certification of exhaust emissions of nonroad diesel engines over 37 kW, three engine duty cycles were defined for an agricultural tractor, a backhoe-loader and a crawler tractor based on the real in-use data. It should be noted that relative times spent in these activities for these three pieces of nonroad equipment are provided by the equipment manufacturers [8]. In-use driving data of 65 different vehicles from Australia, Europe, Japan and the US was used in a drive train model to transform the worldwide transient vehicle cycle (WTVC) into a reference transient engine test cycle called the worldwide harmonized transient cycle (WHTC) by the Working Party of Pollution and

Energy of the U.N. Economic Commission for Europe (UNECE) [9]. A research group from West Virginia University (WVU) proposed four engine duty test cycles: creep, transient, cruise and high-speed for heavy-duty diesel engines developed from the collected data which uses a pre-defined E-55/59 HHDDT chassis test mode to simulate in-use HHDDT operation in California [10] [11]. Similarly, Ullman [8] developed a heavy-duty engine test cycle representative of on-highway not-to-exceed operation [12].

The process used for developing an engine duty cycle from on-road driving data of 11 trucks utilized in shale gas development is presented in the following sections. Section 2 describes a data logging system developed to collect on-board Engine Control Unit (ECU) broadcast information, such as engine speed, load, fuel consumption, pedal position and other relevant parameters. Furthermore, the detailed methodology and entire procedure of generating a target engine duty cycle is demonstrated in Section 3. In Section 4, the final engine duty cycle is achieved and statistically analyzed based on the real-world data collected. Lastly, conclusions to this investigation are presented in Section 5.

2. On-Road Data Acquisition for Heavy-Duty Vehicles

The process of developing a representative engine duty cycle started with the recording of real world driving data from on-road vehicles. J1939 Mini Loggers from HEM Data were used to collect data for vehicles involved in well pad construction, water hauling, and sand hauling in the unconventional well development industry, as shown in **Figure 1**. These loggers are capable of recording J1708 or J1939 parameters along with GPS data. Seven companies participated in the efforts; all were located in the greater Marcellus and Utica Shale regions of the Appalachian Basin. Their operating routes are shown in **Figure 2**. A summary of the vehicle and engine types logged in this study is provided in **Table 1**. Consequently, a total of 11 vehicles were used to develop the on-road cycle. Invalid data files such as those that were short (less than 30 minutes) and did not show activities (parked/service) were excluded. Over 600 hours of data was considered valid and were used for cycle development.

Figure 1. HEM Mini Data Logger.

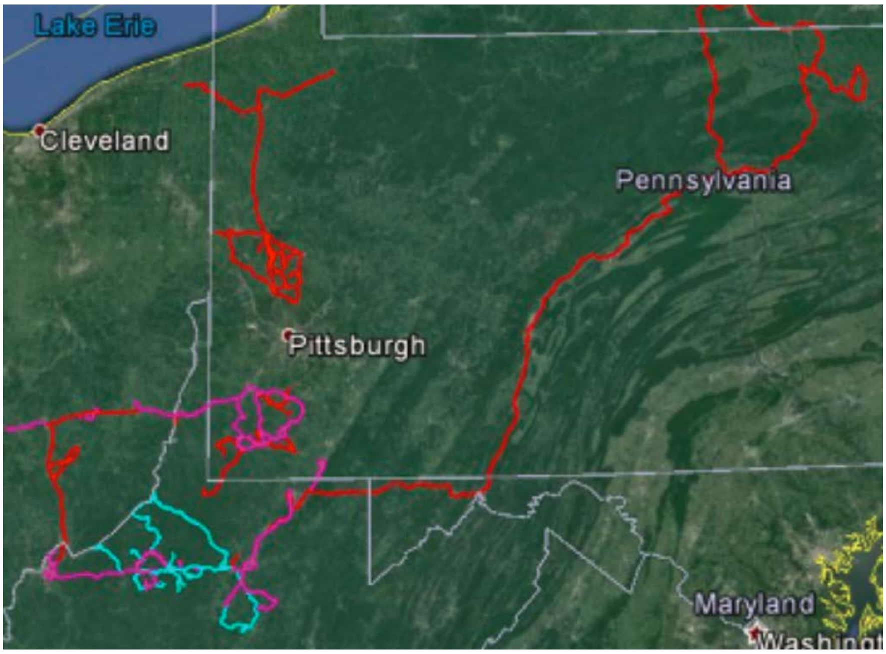

Figure 2. Marcellus and Utica vehicle routes.

Table 1. Water and sand hauling trucks involved in investigation.

Basic Information		Truck/Engine Information			
Truck #	Service	Make	Model	Size (hp)	Year
1	Water Hauling	Cummins	ISX-15	500	2012
2	Water Hauling	Mack	MP8	505	2011
3	Water Hauling	Cummins	ISX-15	500	2012
4	Pad Construction	Volvo	D13	435	2002
5	Sand Hauling	Cummins	ISX-15	500	2013
6	Sand Hauling	Cummins	ISX-15	500	2013
7	Sand Hauling	Cummins	ISX-15	500	2009
8	Sand Hauling	Cummins	ISX-15	500	2008
9	Water Hauling	Caterpillar	C-15	550	2012
10	Water Hauling	Cummins	ISX-15	500	2013
11	Water Hauling	Caterpillar	C-15	550	2009

3. Methodology of Engine Duty Cycle Development

3.1. Outline of Engine Duty Cycle Development

The entire process of the methodology used for representative engine duty cycle development is presented in the flowchart seen in Figure 3. It involves:

- Construction of a database to store the data set comprising of 45 driving trips selected from logging data of all test trucks, formation of a base trip based on this data set and creation of evaluation metrics for the engine duty cycle.
- Segmentation of each driving trip into micro trips (total of 1973) and compression of the long duration micro trips into corresponding micro trips with

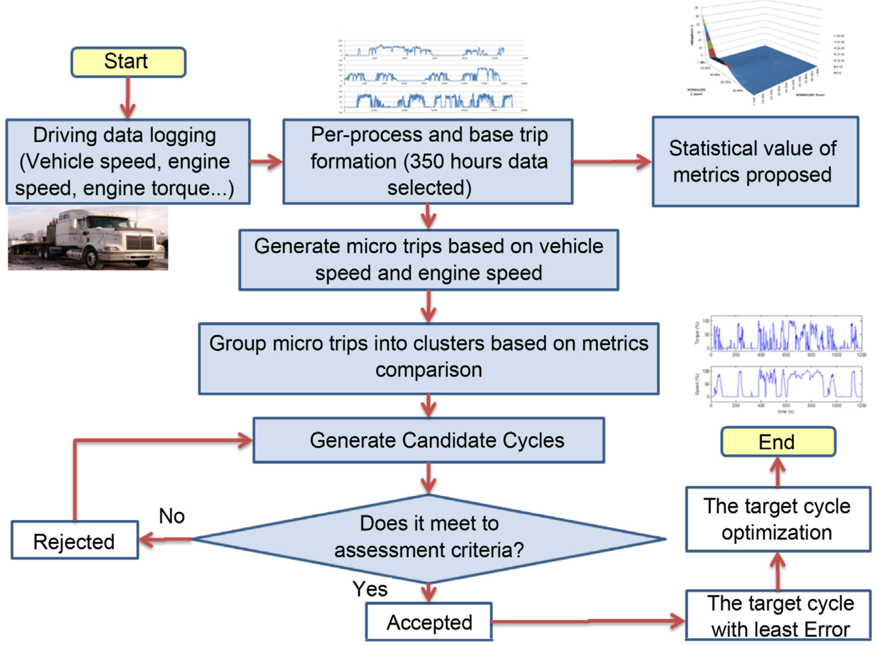

Figure 3. Flowchart of the engine duty cycle development.

appropriate duration. Each micro trip is composed of an idle period and an operation period.

- A number (k) of micro trips were selected as "seed" micro trips, which have the least discrepancy compared to the base trip. Consequently, k groups are established based on clustering possible group members from all other micro trips (1973-k) for each group by comparing the difference of a corresponding characteristic value between the candidate micro trip and seed micro trip.
- Generation of candidate cycles from combined micro trips and calculation of the integrated difference value between each candidate cycle and the base trip using evaluation metrics. If no candidate cycle met the assessment criteria, a new candidate cycle was generated.
- Optimization of the aimed engine duty cycle in terms of the characteristics of data of the FTP heavy-duty diesel transient cycle. It must be noted that the engine duty cycle achieved is a pair of engine speed-time and torque-time traces.

3.2. Normalizing Engine Torque and Speed

As discussed in the Section 2, 11 trucks with 4 different heavy-duty diesel engines were instrumented for data collection. To define the target representative engine duty cycle, engine speed and engine torque observed from the ECU for each truck were normalized according to the requirement of the Code of Federal Regulations (CFR) 40 Part 86 [13]. The $\%speed$ and $\%torque$ are defined by Equations (1) and (2) [10].

$$\%speed = 100\% * \left(speed_{actual} - speed_{curb_{idle}}\right) / \left(speed_{rated} - speed_{curb_{idle}}\right). \quad (1)$$

$$\%torque_{rpm} = 100\% * \left(torque_{rpm_{actual}}\right) / \left(torque_{rpm_{\max}}\right). \quad (2)$$

The actual ECU broadcast engine speed was a reliable and accurate measurement to use for *%speed* [12]. With the "rated speed" data manufacture provided, the value of *%speed* for each data point is obtained. The error of *%speed* may come with the value of "curb idle speed", which is taken as average idle engine speed herein. Since both parameters of "Actual Engine - Percent Torque (%)" and "Nominal Friction - Percent Torque (%)", observed in the ECU broadcast information, are indicated as a percent of reference engine torque according to the definitions in SAEJ1939-71, the specific value of "Actual Torque" is obtained using Equation (3).

$$\%torque_{rpm_{actual}} = \left(\%torque_{eng} - \%torque_{fri}\right) * torque_{ref}. \quad (3)$$

It should be noted that "Actual Engine - Percent Torque (%)", "Nominal Friction - Percent Torque (%)" and reference engine torque are expressed as $\%torque_{eng}$, $\%torque_{fri}$ and $\%torque_{ref}$, respectively. Using engine lug curves (*Maximum* $torque_{rpm}$ obtained) and reference engine torques offered by the manufacturers, the $\%torque_{rpm}$ of every point was calculated.

3.3. Engine Duty Cycle Generation

In order to evaluate the exhaust emission and fuel consumption of the trucks tested, an engine bench test should be applied in a controlled laboratory test environment. Thus, a representative engine duty transient cycle derived from data collected from the engines tested was developed. At the same time, a computer program utilizing Visual Basic and Microsoft SQL Server Database was used to implement the methodology proposed.

3.3.1. Construction of a Reference Base Trip

Twenty days of data were recorded from the 11 trucks analyzed resulting in 500 files. Each file is defined as an individual trip, and not all trips are accepted due to the reasons of too short time duration or limited activities. Finally, a data set comprised of 45 trips with a total of 1,285,655 second-by-second data points and about 357 hours running duration was selected manually to form the entire base trip. The variables of time, vehicle speed, engine speed, actual engine-percent torque (%) and nominal friction -percent torque (%) contained in the file are transmitted into the database. It should be noted that points with zero vehicle speed and zero engine speed, implying engine shutdown with parking status, are filtered out. Also, the parameters of *Norm_ESpeed* (Normalized Engine Speed %), *Norm_ETorque* (Normalized Engine Torque %), *E_Accel* (Engine Speed Acceleration %) and *T_Accel* (Engine Torque Acceleration %) are defined and calculated for each point, according to Equations (4) and (5).

$$E\_Accel = Norm\_ESpeed_{current} - Norm\_ESpeed_{previous}. \quad (4)$$

$$T\_Accel = Norm\_Etorque_{current} - Norm\_Etorque_{previous}. \quad (5)$$

3.3.2. Micro-Trip Generation

Each trip is segmented into a certain number of micro-trips, which is comprised of an engine idling period and an engine operating period. The engine idling period was defined by data points for which the vehicle speed was lower than 5 kph and the engine speed was lower than the average engine speed (*E_Speedave*) at zero vehicle speed. The value of *E_Speedave* was obtained by statistics considering possible pumping activity for trips concerned. Pumping activities were performed when the engine powers an apparatus to pump sand or water while vehicle was stationary. Thus, 1973 micro trips are identified from 45 individual trips.

One expectation of the target engine duty cycle was that it should be 2400 seconds at most and be composed of at least eight micro trips. The duration time of longest trip is limited to 400 seconds and any micro trip with a time over 270 seconds was compressed on the consideration of the statistical value of *Pnt_Idle* (definition seen in the below paragraph). This means one point among several consecutive points should be chosen to represent the related points. Therefore, the method of least-square errors of *Norm_ESpeed* and *Norm_ETorque* was used to guarantee that characteristics of the new micro-trip best represented the original longer trip. Furthermore, the assessment metrics for each micro-trip included the following parameters:

1) *Pnt_Idle*, Percentage of the entire micro-trip that is idle (%)

a) $Pnt\_Idle = 100 \times \left(T_{\text{whole}} - T_{\text{operation}}\right) / T_{\text{whole}}$

b) T_{whole}: whole duration time of the micro-trip;

c) $T_{operation}$: operating time of the micro-trip.

2) *Pnt_Accel*, Portion of the whole micro-trip of engine acceleration (%)

d) When *E_Accel* > 1.8%, means that the engine revolution accelerates more than 30 rpm per second.

e) $Pnt\_Accel = 100 \times T_{accel} / T_{\text{operation}}$

f) T_{accel}: total duration of engine acceleration for the micro-trip.

3) *Pnt_Cruise*, Portion of the whole micro-trip of engine steady running (%)

g) When −1.8% ≤ *E_Accel* ≤ 1.8%, means that the change of engine revolution speed is under 30 rpm per second.

h) $Pnt\_Cruise = 100 \times T_{\text{cruise}} / T_{\text{operation}}$

i) T_{cruise}: total duration of engine running in cruise status for the micro trip.

4) *Ave_Accel*, the average value of *E_Accel* for the acceleration mode when *E_Accel* > 1.8% (%)

5) *Ave_Decel*, the average value of *E_Accel* for the deceleration mode when *E_Accel* < −1.8% (%)

6) *Ave_Cruise*, the average value of *E_Accel* for the cruise mode when −1.8% ≤ *E_Accel* ≤ 1.8% (%)

7) *Ave_ESpeed*, the average value of normalized engine speed (*Norm_ESpeed*) in operation period for the micro-trip (%)

8) *Ave_Torque*, the average value of normalized engine torque (*Norm_Etorque*) in operation period for the micro-trip (%)

9) *Dev_ESpeed*, the standard deviation value of normalized engine speed

($Norm\_ESpeed$) for the micro-trip (%)

10) $Dev\_ETorque$, the standard deviation value of normalized engine torque ($Norm\_Etorque$) for the micro-trip (%)

11) $Ave\_Difference$, the average value of the corresponding above ten parameters' difference between the micro-trip and the base trip.

a) $$Ave\_Difference = \left(Difference_{Pnt\_idle} + Difference_{Pnt\_accel} + L + Difference_{Dev\_Etorque}\right) / 10$$

b) $$Difference_{Pnt\_idle} = \left(Pnt\_idle_{mirco\_trip} - Pnt\_idle_{base\_trip}\right) / Pnt\_idle_{base\_trip}$$

3.3.3. Group Micro Trips

All 1973 micro-trips were sorted in ascending order by the $Ave\_Difference$ value, which means micro-trips in the top position have characteristics closer to that of the base trip. Thus, the top k micro-trips were chosen as "seed" micro-trips. The seed micro-trip was used as a reference to select other member micro-trips to generate the corresponding group. The seed micro-trip for $Group_i$ was noted as $Seed_i$. Next, member micro-trips for each group were collected from all other micro-trips (1973-k) by comparing the difference of value of the corresponding parameter between the candidate micro-trip and the seed micro-trip, respectively. If all absolute comparative differences of the eight parameters' value (including Pnt_idle, Ave_Accel, Ave_Decel, Ave_Cruise, Ave_ESpeed, Ave_Torque, Dev_ESpeed and $Dev\_ETorque$) was lower than an error threshold value, the micro-trip in question was added as a member of the corresponding group. For instance, the micro-trip $MTrip_j$ was considered part of the $Group_i$, if the following conditions were met:

$$100\% \times \text{abs}\left(Pnt\_idle_j - Pnt\_idle_{seedi}\right) / Pnt\_idle_{seedi} \le \text{Error}$$

$$100\% \times \text{abs}\left(Ave\_Accel_j - Ave\_Accel_{seedi}\right) / Ave\_Accel_{seedi} \le \text{Error}$$

$$100\% \times \text{abs}\left(Ave\_Decel_j - Ave\_Decel_{seedi}\right) / Ave\_Decel_{seedi} \le \text{Error}$$

$$100\% \times \text{abs}\left(Dev\_ETorque_j - Dev\_ETorque_{seedi}\right) / Dev\_ETorque_{seedi} \le \text{Error}$$

Therefore, all the member micro-trips of groups had similar characteristics of the seed micro-trip. If the group i had n_i member micro trips, n_i was defined as the number of micro-trips for the $Group_i$. Obviously, with an increasing error value, more micro-trips will be grouped into members and result in more computing time consumption. The number of comparison parameters also affects the member scale for every group.

3.3.4. Establishment of Candidate Cycles

The possible candidate cycle was made up of k micro-trips from different groups. Every micro-trip was selected from a different group. Thus, the number of candidate cycles was $n_1 \times n_2 \times n_3 \times, \cdots, n_{k-1} \times n_k$. For this study, the value of k was eight and the values of $n_1, n_2, n_3, \cdots, n_8$ were 6, 3, 15, 1, 3, 5, 28 and 2. The total number of possible candidate cycles was 226,800 from which the best representative target cycle was selected.

For each candidate cycle and individual trip, the assessment metrics were established similarly to those that defined the micro-trips.

1) *Pnt_Idle*, Portion of the whole cycle that is idle (%)

a) $Pnt\_Idle = 100 \times \left(Idle\_Time_1 + Idle\_Time_2 + \cdots + Idle\_Time_k \right) / T_{total}$, where $Idle\_Time_k$ means the sum of idle period time of the micro-trip $MTrip_k$ and T_{total} means the total time of cycle related.

2) *Pnt_Accel*, Portion of the operating condition experiencing engine acceleration (%)

a) $Pnt\_Accel = 100 \times \left(T_{accel\_1} + T_{accel\_2} + \cdots + T_{accel\_k} \right) / T_{total}$, T_{accel_k} stands for the total time of engine acceleration for the micro-trip $MTrip_k$.

3) *Pnt_Cruise*, Portion of the operating condition experiencing engine steady running (%)

a) $Pnt\_Cruise = 100 \times \left(T_{cruise\_1} + T_{cruise\_2} + \cdots + T_{cruise\_k} \right) / T_{total}$, T_{cruise_k} stands for the total time of engine cruise for the micro-trip $MTrip_k$.

4) *Ave_Accel*, the average value of *E_Accel* when *E_Accel* > 1.8% in the whole cycle (%)

5) *Ave_Decel*, the average value of *E_Accel* when *E_Accel* < −1.8% in the whole cycle (%)

6) *Ave_Cruise*, the average value of *E_Accel* when −1.8% ≤ *E_Accel* ≤ 1.8% in the whole cycle (%)

7) *Ave_ESpeed*, the average value of *Norm_ESpeed* for operation periods in the whole cycle (%)

8) *Ave_Torque*, the average value of *Norm_Etorque* for operation periods in the whole cycle (%)

9) *Dev_ESpeed*, the standard deviation value of *Norm_ESpeed* for operation periods in the whole cycle (%)

10) *Dev_ETorque*, the standard deviation value of *Norm_Etorque* for operation periods in the whole cycle (%)

The ten parameters of base trip are calculated under the assumption that the base trip was a particular trip containing 1973 micro-trips. Finally, the integrated difference (noted as *Int_Difference*) of each candidate cycle is evaluated as:

$$Int\_Difference_i = \left(Diff\_Pnt\_Idle_i + Diff\_Pnt\_Accel_i + L + Diff\_Dev\_Power_i \right) / 10$$

where,

$$Diff\_Pnt\_Idle_i = 100 \times \text{absolute}\left(Pnt\_Idle_i - Pnt\_Idle_{base\_trip} \right) / Pnt\_Idle_{base\_trip}$$

$$\begin{aligned} & Diff\_Pnt\_Accel_i \\ & = 100 \times \text{absolute}\left(Pnt\_Accel_i - Pnt\_Accel_{base\_trip} \right) / Pnt\_Accel_{base\_trip} \end{aligned}$$

$$\begin{aligned} & Diff\_Dev\_ETorque_i \\ & = 100 \times \text{absolute}\left(Dev\_ETorque_i - Dev\_ETorque_{base\_trip} \right) / Dev\_ETorque_{base\_trip} \end{aligned}$$

The desired cycle was defined as the one with the smallest value of *Int_Difference*, which carries the most similar characteristics of the entire base trip and can be representative of the real-world operation of engines involved.

3.3.5. Optimization for the Target Cycle

One of rules applied to the target engine duty cycle was that the maximum and minimum value of *E_Accel*, *T_Accel* for the cycle should not exceed the respective value of the standard FTP heavy-duty diesel transient cycle. An optimization approach was applied to smooth the target cycle by inserting additional points from the original set of data points into the related micro-trip. It is noted that the acceptable additional points must be selected from sampled data of the same vehicle. This ensured that the data spliced in was of the same type of operation.

4. Results

Employing the methodology described above, a target engine duty cycle with 2291 data points was developed with an *Int_Difference* value of 9.9%. The specific values of the assessment metrics are shown in **Table 2**. When emphasis was placed on the differences of *Ave_ESpeed*, *Ave_Torque*, *Dev_ESpeed* and *Dev_ETorque* between the target cycle and base trip, the average error for the four parameters was shown to be 2.05%, demonstrating the effectiveness of the methodology in matching the actual engine operating behavior statistically. The reason there was such a large difference regarding the *Pnt_Accel* value was because the parameter was not involved in comparison during the process of selecting member micro-trips for the group. More parameters lead to fewer members due to the increasingly strict requirement.

Table 2. Specific values of assessment metrics for the base trip and target duty cycle.

Metric	Unit	Cycle 83,359	Base Trip	Error (%)
TOTAL_TIME	(s)	2291	1,285,655	-
Int_Difference	(%)	9.9	-	-
Pnt_Idle	(%)	28.1	30.1	6.9
Pnt_Accel	(%)	13.8	8.2	68.8
Pnt_Cruise	(%)	45.1	44.1	2.2
Ave_Accel	(%)	6.0	5.5	9.1
Ave_Decel	(%)	6.2	6.0	3.6
Ave_Cruise	(%)	0.02	0.02	0
Ave_ESpeed	(%)	41.9	41.4	1.0
Ave_Torque	(%)	17.6	17.8	0.94
Dev_Espeed	(%)	11.1	11.5	3.1
Dev_ETorque	(%)	22.2	21.6	3.2

The maximum and minimum values of *E_Accel*, *T_Accel* for the standard FTP heavy-duty diesel transient cycle are listed statistically as follows.

MAX_*E_Accel* (%): 37.24

MIN_*E_Accel* (%): −31.55

MAX_*T_Accel* (%): 78.53

MIN_*T_Accel* (%): −84.92

A total of 11 points where the *E_Accel*, *T_Accel* values exceeded the mentioned limitation were screened out. By inserting 30 additional points into cycle 83,359, the final cycle was optimized to satisfy the requirement of work of the engine test. For the selected best performing cycle developed, the normalized engine speed and engine torque versus time traces, containing a total of 2321 points, are displayed in **Figure 4**. Moreover, the distributions of normalized engine speed and torque for the target cycle and base trip are analyzed statistically in **Table 3** and compared with corresponding curves shown in **Figure 5**. The comparison of normalized engine speed and torque frequency distributions for the target cycle and base trip are presented in **Figure 6**. Note that negative engine torque is not included in the statistics. Finally, based on the specific parameters of the target engine to be tested in laboratory, the above normalized engine speed and engine torque can be denormalized into specific values, which are to be used for engine bench testing.

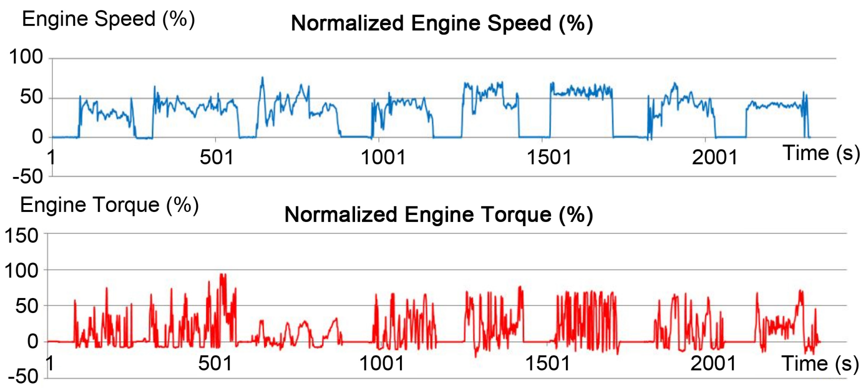

Figure 4. Curves for the target duty cycle with normalized engine speed and torque.

Table 3. Distribution of normalized engine speed and torque for the target cycle and based trip (percentage of cycle in each normalized engine speed or torque bin).

Value	Engine_Speed		Engine_Torque	
	Cycle 83359	Base Trip	Cycle 83359	Base Trip
0% - 10%	29.73	31.65	60.92	67.43
10% - 20%	2.15	5.27	9.87	7.78
20% - 30%	7.88	8.75	10.60	5.68
30% - 40%	17.75	13.56	6.08	4.41
40% - 50%	23.78	17.34	3.66	3.31
50% - 60%	11.63	13.80	3.19	2.77
60% - 70%	6.85	6.82	4.61	5.76
70% - 80%	0.22	2.38	0.60	1.91
80% - 90%	0	0.37	0.22	0.57
90% - 100%	0	0.06	0.26	0.39

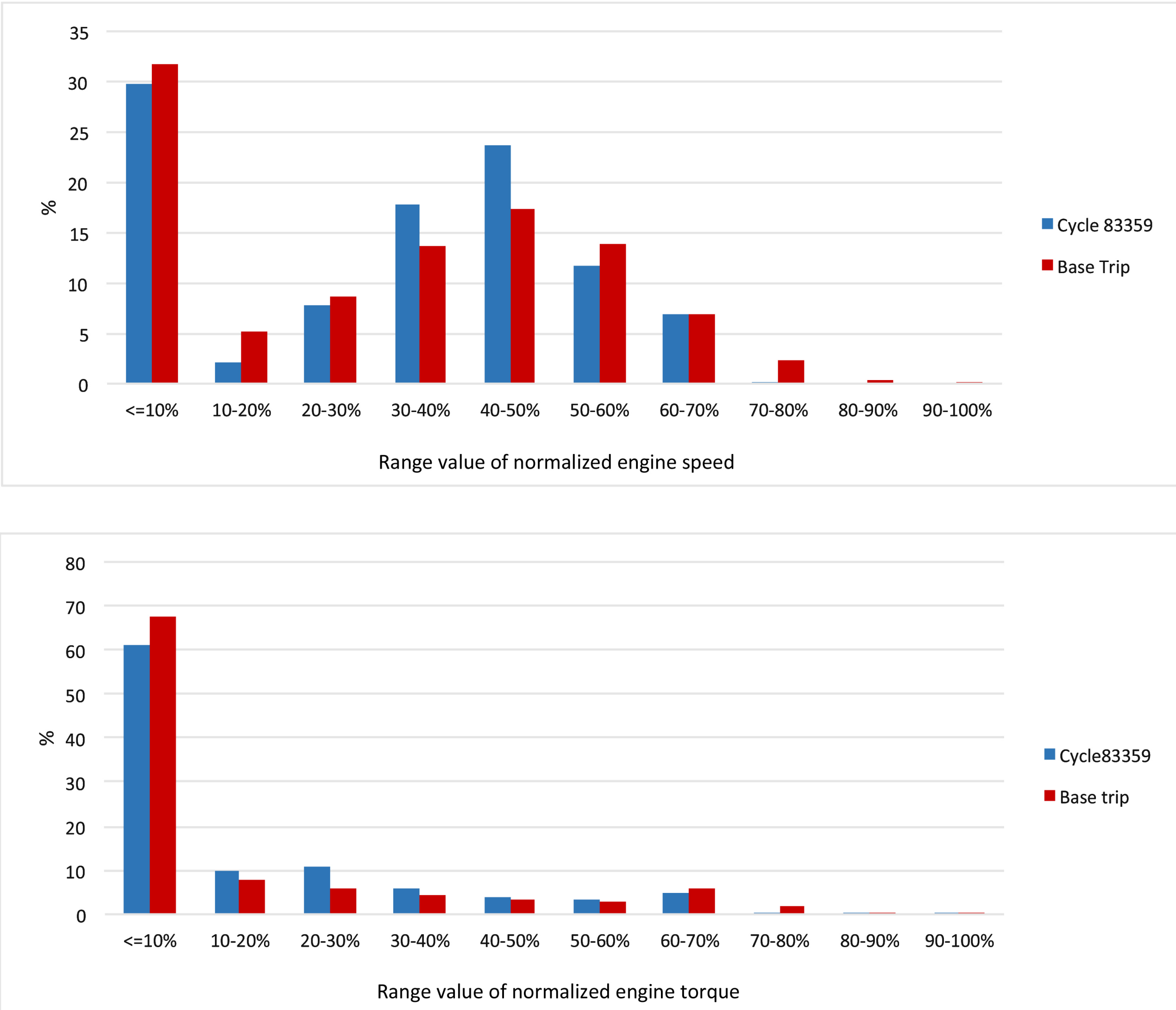

Figure 5. Distribution curves of normalized engine speed and torque for the target cycle and base trip.

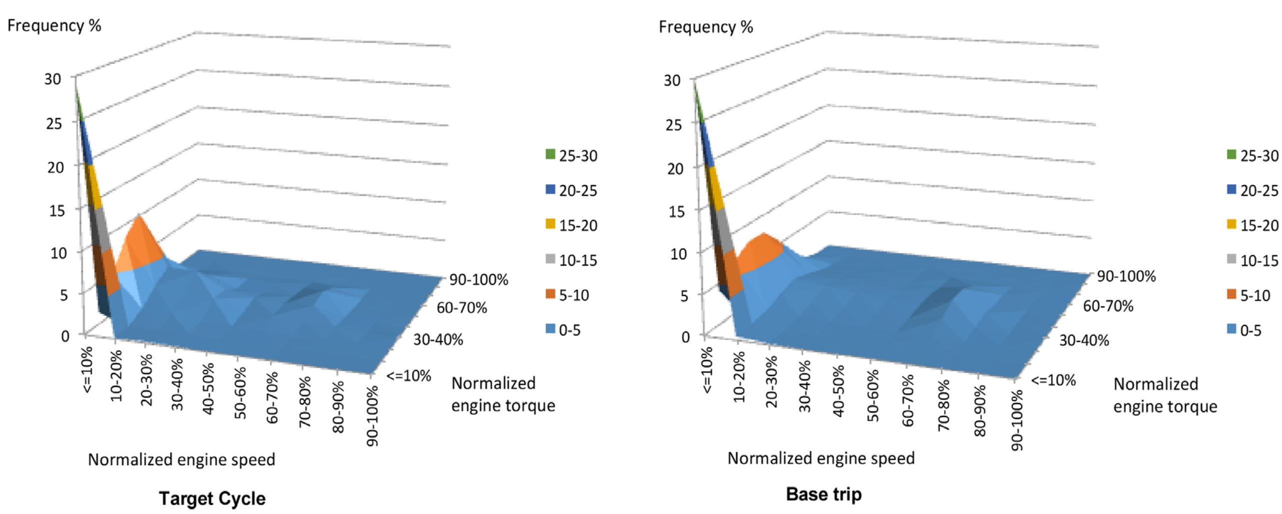

Figure 6. Comparison of normalized engine speed and torque frequency distribution for the target cycle and base trip.

5. Conclusions

A method for the development of a normalized engine transient duty cycle was developed using micro-trips extracted from data logged from on-road heavy-duty vehicles. The specific values of engine speed and engine torque were normalized for all sampled data points from different engines as defined by the CFR §86.1333-90. The assessment metrics for the micro-trip and candidate cycles included ten parameters related to the engine working conditions. These metrics were designed to evaluate the inherent characteristics of the engine behavior. By comparing developed cycles to the base trip, a representative cycle was achieved with an acceptable low integrated difference. Therefore, the proposed approach was expected to be a feasible representation of heterogeneous engine behavior for trucks working in a particular area of operation. However, to examine the feasibility and suitability, the developed engine duty cycle should be run on an engine dynamometer and the values of exhaust emissions and fuel consumption compared to real world conditions.

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