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DEVELOPMENT AND DEMONSTRATION OF ADVANCED METHODS FOR QUANTIFYING FREIGHT TRUCK ACTIVITY, ENERGY USE, AND EMISSIONS

Final Report

by

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EXECUTIVE SUMMARY

A simplified version of EPA's MOVES model was developed for heavy duty trucks and incorporated into the MOVES Lite framework established by Liu and Frey (2013). MOVES light is based on dividing vehicle speed trajectories into Operating Mode (OpMode) bins. OpMode bins are defined for braking, idling, and three speed ranges of 0 to 25, 25 to 50, and over 50 mph. For each speed range, there are OpMode bins for coasting and for various levels of engine power demand. Engine power demand is quantified based on scaled tractive power (STP), which is a function of 1 Hz speed, acceleration, and grade. Here, MOVES Lite is developed for short-haul trucks (SHTs) and Long-Haul Trucks (LHT). SHTs include Class 6 and 7 trucks of 19,500 lbs to 33,000 lbs gross vehicle weight rating (GVWR), and LHTs include Class8a and Class 8B trucks of over 33,000 lbs GVWR.

For SHT and LHT, effective OpMode rates were estimated for vehicles that are 0, 5, 7, 9, 10, 15, 20, and 30 years old, to represent the timing of implementation of emission standards. The effective OpMode rates for emissions of HC, CO, NO_x, and $PM_{2.5}$ differ substantially with vehicle age. For example, for SHT, the emission rates for 0 year old vehicles are only 3.6%, 4.6%, 2.2%, and 0.10% of the rates for 30 year old vehicles for HC, CO, NO_x, and $PM_{2.5}$, respectively. These differences in emission rates are based on the implementation of emission control technologies such as exhaust gas recirculation (EGR), diesel oxidation catalyst (DOC), diesel particle filter (DPF), and selective catalytic reduction (SCR).

Base emission and energy use rates for the Federal Test Procedure (FTP) cycle are used in MOVES Lite as a basis for calibrating MOVES Lite to MOVES. For HC, NO_x, and CO, the MOVES estimates of base emission rates are shown to typically decrease with decreasing age in a step-wise manner for both SHT and LHT. These step decreases in emission rates are associated with the implementation of successively more stringent vehicle emission standards. $PM_{2.5}$ emission rates typically decrease from older to newer vehicles. Energy use rates are consistently higher for the larger, heavier LHT versus SHT.

MOVES includes 13 default driving cycles for SHTs and 13 default driving cycles for LHTs. The LHT default cycles are, in most cases, different than those for SHT. The range of average speeds for the default cycles are similar for the two vehicle types, ranging from 1.77 mph to 77.8 mph for SHT and from 1.77 mph to 76.7 mph for LHT. However, the range of cycle average STP is different, ranging from 0.0.4 skW/Mt to 5.21 skW/Mt for SHT and 0.10 skW/Mt to 11.64 skW/Mt for LHT. Although the speed profiles are not very different between the SHT and LHT default cycles, the cycle average STP tends to be higher for LHT. This is because the rolling resistance coefficient, rotating resistance coefficient, drag coefficient, and source mass factor are greater for LHT than for SHT. Thus, for a given speed and acceleration, STP tends to be greater for LHT than for SHT.

Typically, the cycle average HC and CO emission rates decrease with increasing cycle average speed for both SHT and LHT and for every vehicle age. Both cycle average speed and vehicle age are important determinants of cycle average emission rates. Cycle average NO_x emission rates are variable with cycle average speed and with vehicle age. The relative differences in these rates are greater with respect to age than with respect to cycle average speed. The cycle average NO_x emission rates reach a minimum around 60 mph, and increase slightly with higher speeds that are greater than 60 mph. Cycle average $PM_{2.5}$ emission rates are far more sensitive to vehicle age than to vehicle speed. These rates differ by more than three orders of magnitude when comparing 0 year old to 30 year old vehicles for a given cycle. The range of variability among driving cycles for a given age is less than an order-of-magnitude. The trends in energy use rates and CO_2 emission rates are similar. FThe rates reach a minimum at approximately 60 mph, and increase with higher speeds.

With average errors of 0.08 percent for SHT and 0.02 percent for LHT, and errors for individual cycle average rates not exceeding ±0.5 percent, MOVES Lite is shown to accurately predict emission rates for SHT and LHT compared to MOVES. Because many of the factors to which MOVES is sensitive are approximately constant during the time period of a typical TDM or TSM simulation, there is no need to run MOVES in its entirety for every link in a network. Thus, MOVES Lite is suitable for further use as a simplified alternative to MOVES, especially for integration with traffic simulation models such as DTAlite.

1.0 INTRODUCTION

Freight movement entails consumption of a large amount of energy and production of significant amount of air pollution, which has local and regional air quality impacts that can be of regulatory significance in many parts of the country. Non-attainment of air quality standards automatically triggers requirements to reduce emissions that entail control costs and thus may affect economic growth regionally; thus, preventive management of air pollution can yield substantial economic benefits. Furthermore, reduction of air pollution reduces external economic damages such as adverse effects on human health and ecosystems. Thus, key metrics of freight efficiency should include intensity of energy use and emissions (e.g., gallons of fuel consumed, or lbs of pollutants emitted, per ton-mile of freight). Furthermore, heavy duty trucks can contribute substantially to traffic congestion because of their large size, different performance, and typical activities, compared to light duty vehicles. In this work, we develop a new tool to quantify heavy duty vehicle energy use, and emissions to enable development of more effective policy options for reduced congestion and improved energy and emissions efficiency of truck freight transport.

Heavy duty trucks are a key freight transportation mode and are responsible for substantial consumption of energy, emissions of pollutants harmful to human health including nitrogen oxides (NO_x), particulate matter (PM), and greenhouse gas emissions, particularly carbon dioxide (CO_2). Freight trucks operate as part of a mix of vehicles, and thus interact with vehicle traffic in complex ways. Simulation-based large-scale traffic simulation models are widely used for better planning and operating traffic systems on a large-scale regional network involving both passenger cars and heavy duty trucks. Mesoscopic dynamic traffic assignment and simulation models, such as DTALite, are capable of capturing the traveler's route choice and modeling different scales of networks under various transportation management strategies, such as various road pricing and adaptive traffic signal controls (Zhou et al., 2015). As an open-source traffic network flow simulator, DTALite uses simplified Newell's car following model to generate second-by-second mesoscopic trajectories and then further communicate with MOVES Lite to produce a wide range of mobility and environmental Measure of Effectiveness (MOE) for different types of on-road vehicles, for example, passenger cars, passenger truck and heavy duty trucks.

Because many of the factors to which MOVES is sensitive are approximately constant during the time period of a typical TDM or TSM simulation, there is no need to run MOVES in its entirety for every link in a network (Frey and Liu, 2013). The emissions model, MOVES Lite, is based on data used in the U.S. Environmental Protection Agency's MOVES emissions factor model, but runs over 3,000 times faster. However, as yet, no such tool is available for heavy duty traffic simulation and estimation of the effect of heavy duty vehicle activity on energy use and emissions concurrently with light duty vehicles. Such a tool would enable assessment of traffic and transportation control measures, as well as policies specifically aimed at heavy duty trucks (e.g., idle reduction), with respect to regional-scale energy use and emissions.

The objective of this project is to develop a simplified microscale model, MOVES Lite, for estimation of energy use and emissions of heavy duty freight trucks based on 1 Hz speed trajectories.

2.0 METHODS

MOVES Lite is a simplified version of the energy and emission estimation model Motor Vehicle Emission Simulator (MOVES). MOVES Lite estimates vehicle energy and emission rates following a simplified and efficient approach. The approach reduces data intensive computation, and thus reduces the overall data processing, and operational time and effort. MOVES Lite includes 2 freight vehicle types, which are single-unit short haul truck (SHT), and combination long haul truck (LHT). This chapter includes technical details of the model, including identification of vehicle types, method for estimation of operating modes, method for estimation of cycle average energy use and emission rates, key inputs for the model, key outputs of the model, and the approach for model verification.

2.1 VEHICLE TYPES

MOVES Lite is based on selected vehicle types found in MOVES. MOVES defines vehicle types based on two classification schemes: (a) Highway Performance Monitoring System (HPMS) classification based on vehicle physical characteristics, activity, and usage pattern; (b) U.S. Environmental Protection Agency (EPA) classification for emission standards based on Gross Vehicle Weight Rating (GVWR) (EPA, 2016a). GVWR is defined as the maximum combined weight of the vehicle and its load. The HPMS based vehicle classes are referred to as "source use types" or simply "source types". The EPA standards based vehicle classes are defined as "regulatory classes" in MOVES. A given source type often falls under multiple regulatory classes, and each of them may have different emission rates. Thus, MOVES Lite includes a detailed vehicle classification based on combinations of source types, regulatory classes, and fuel types.

MOVES contains a default input database which is managed through a MySQL database, and includes multiple data tables with default input values (EPA, 2010). The nationwide existing proportions of source type, regulatory class, fuel type, and engine technology were taken from MOVES2014a default database table '**SampleVehiclePop**'. The vehicle types are defined in MOVES Lite based on the proportions of such combinations. The selected model year is 2015. Table 1 lists the vehicle types defined for MOVES Lite. The column "Default Fractions" in Table 1 indicates the proportions of source type, regulatory class, fuel type, and power train combinations for each defined vehicle types. The associated source types, power train and fuel types with respective identifiers are listed in Table 2. The associated regulatory class definitions are given in Table 3.

Table 1: MOVES Lite Freight Vehicle Types

Source type[1] (Source type ID)	Regulatory class[2] (Regulatory class ID)	Power train and fuel type[1] (Power train and fuel type ID)
Single-unit short haul truck (52)	MHD67 (46)	Conventional Diesel (2)
Combination long haul truck (62)	HHD8 (47)	Conventional Diesel (2)

[1] Power train and fuel types with identifiers (ID) are given in Table 2; [2] Regulatory class descriptions are given in Table 3.

Table 2: Freight vehicle source types, power train and fuel types included in MOVES Lite

Source type	Source type ID*	Power train and fuel type	Power train and fuel type ID
Single-unit short haul Truck	52	Conventional Diesel	2
Combination long haul truck	62	Conventional Diesel	2

* Source: Reference (1)

Table 3: Regulatory class definitions for the freight vehicle types in MOVES Lite

Regulatory Class Name	Regulatory Class ID	Definition
MHD67	46	Medium-heavy duty: Class 6 and 7 Trucks (19,500 pounds < GVWR* ≤ 33,000 pounds)
HHD8	47	Heavy-heavy duty: Heavy-heavy duty: Class 8a and 8b Trucks (GVWR* > 33,000 pounds)

Source: Reference (1) * GVWR: Gross Vehicle Weight Rating; ** MOVES takes Urban bus definition from Code of Federal Regulations (CFR) section 86.091-2

2.2 OPERATING MODES

MOVES Lite is based on the same 23 operating modes (OpModes), used in MOVES. OpModes are defined based on braking, idling, and three speed ranges (EPA, 2015a&b). Within the speed ranges, there are OpModes based on ranges of Vehicle Specific Power (VSP) for light duty vehicles, and Scaled Tractive Power (STP) for heavy duty vehicles. VSP is estimated by normalizing the total vehicle power demand by its weight (4). In MOVES, and thus in MOVES Lite, second-by-second VSP is estimated as (EPA, 2015a):

$$VSP = \frac{(A_{TR,v} \times v_t) + (B_{RR,v} \times v_t^2) + (C_{AD,v} \times v_t^3) + \{M_v \times v_t \times (a_t + gr_t)\}}{M_v} \quad (1)$$

Where,

$A_{TR,v}$ = tire rolling resistance coefficient (kW-s/m) for vehicle type v;

$B_{RR,v}$ = rotational resistance coefficient (kW-s^2/m^2) for vehicle type v;
$C_{AD,v}$ = aerodynamic drag coefficient (kW-s^3/m^3) for vehicle type v;
v_t = instantaneous vehicle speed (m/s) at time t;
a_t = instantaneous vehicle acceleration (m/s^2) at time t, estimated using Equation (3);
g = acceleration due to gravity (9.8 m/s^2);
r_t = road grade (in fraction) at time t;
M_v = mass of the source type (metric tons), referred to as the source mass factor for vehicle type v
v = MOVES Lite vehicle type (as defined in Table 1)
t = time (second)

STP is the total engine power demand scaled by a factor, referred to as scaling factor or fixed mass factor (EPA, 2015b). STP is given by:

$$STP = \frac{(A_{TR,v} \times v_t) + (B_{RR,v} \times v_t^2) + (C_{AD,v} \times v_t^3) + \{M_v \times v_t \times (a_t + g r_t)\}}{f_{scale}} \quad (2)$$

Where,

f_{scale} = scaling factor for heavy duty vehicles (metric tons), also referred to as fixed mass factor

The source mass factor (M_v) is the average weight of a given source type including weight of the vehicle, occupants, fuel, and payload. The fixed mass factor (f_{scale}) is used to bring the range of tractive power into the same range as the VSP values. The coefficients $A_{TR,v}$, $B_{RR,v}$, and $C_{AD,v}$ are referred to as the road load coefficients. The parameters $A_{TR,v}$, $B_{RR,v}$, $C_{AD,v}$, M_v, and f_{scale} are available in MOVES default database table '**SourceUseTypePhysics**' for the source types. Table 4 lists the VSP and STP parameters that are associated with the vehicle types in MOVES Lite. MOVES provides parameter values based on source type.

Table 4: Operating mode parameters for the MOVES Lite freight vehicle types

Source type	**Rolling coefficient, $A_{TR,v}$**	**Rotating coefficient, $B_{RR,v}$**	**Drag coefficient, $C_{AD,v}$**	**Source mass factor, M_v (metric ton)**	**Fixed mass factor, f_{scale} (metric ton)**
Short-Haul Truck (SHT)	0.596526	0	0.00160302	8.53896	17.1
Long-Haul Truck (LHT)	1.47389	0	0.00368164	24.4196	17.1

Source of Data: Table '**SourceUseTypePhysics**' from MOVES2014a default database

A driving cycle is a second-by-second speed trace of the vehicle. Second-by-second acceleration is estimated as the difference between the speed values during two consecutive seconds:

$$a_t = v_{t+1} - v_t \quad (3)$$

Second-by-second VSP estimates for light duty vehicles are estimated using 1 Hz speed, acceleration, and road grade from a specific driving cycle, and the coefficients for a specific source type.

As shown in Table 5, 23 OpModes are defined in MOVES based on specified ranges of VSP (for light duty vehicles) or STP (for heavy duty vehicles), speed, and acceleration (EPA, 2015a).

OpMode 0 represents deceleration/braking. OpMode 1 represents idle. Opmodes 11 and 21 represent coasting at different speed ranges. The other OpModes represent cruising or acceleration within different speed ranges. Deceleration/braking is defined based on only instantaneous acceleration. Idle is defined by instantaneous vehicle speed. The other 21 OpModes are defined based on VSP (for light duty vehicles) or STP (for heavy duty vehicles), and specified ranges of speed. For the coasting OpMOdes, VSP is less than 0. For the cruise/acceleration OpModes, VSP ranges from 0 kW/Metric ton to over 30 kW/Metric ton. The numerical ranges of values for the OpMode bins are the same for VSP and STP. The OpModes weighted by time spent in each bin represent any driving cycle. An OpMode energy rate in mass per time represents the mean energy rate corresponding to that OpMode, and can be weighted by a driving cycle to estimate the cycle average energy rate.

2.3 CYCLE AVERAGE ENERGY USE AND EMISSION RATES

The MOVES Lite model contains a base rate and a correction factor (Frey and Liu, 2013). The base energy use and emission rates account for site-specific characteristics such as geographic region, ambient conditions, and fuel properties. The base rate is the quantity by which the simplified model can be calibrated to MOVES for a particular set of ambient and operational conditions for a given case study. The base energy use and emission rates for each vehicle type are obtained by running MOVES for a base driving cycle, and for specific conditions including a particular geographic region, ambient conditions, fuel properties, and vehicle age distribution. The correction factor accounts for any user-specified driving cycle. These driving cycles can be quantified for any user-specified time period or location. For example, the driving cycle can represent a single vehicle moving on a single road link. MOVES Lite estimates energy use and emission rates based on a time-weighted average of OpMode energy use and emission rates in kilojoules per hour (kJ/hour) that correspond to the source type, regulatory class, fuel type, and power train.

The fleet and cycle average energy use rate for a user-specified driving cycle is given by:

$$CE_c = \sum_v \{ [\sum_a (EF_{b,a,v} \times CCF_{c,a,v} \times f_{a,v})] \times f_v \} \quad (4)$$

Table 5: MOVES Operating Mode (OpMode) Definitions

Operating Mode ID	Operating Mode Description	Vehicle Specific Power, VSP_t (kW/Metric ton)[1]	Scaled Tractive Power, STP_t (kW)[2]	Vehicle Speed, v_t (mph)	Vehicle Acceleration, a_t (mph/sec)
0	Deceleration/ Braking				$a_t \leq -2.0$ or ($a_t < -1.0$ and $a_{t-1} < -1.0$ and $a_{t-2} < -1.0$)
1	Idle			$-1 \leq v_t < 1$	
11	Coast	$VSP_t < 0$	$STP_t < 0$	$1 \leq v_t < 25$	
12	Cruise/ Acceleration	$0 \leq VSP_t < 3$	$0 \leq STP_t < 3$		
13		$3 \leq VSP_t < 6$	$3 \leq STP_t < 6$		
14		$6 \leq VSP_t < 9$	$6 \leq STP_t < 9$		
15		$9 \leq VSP_t < 12$	$9 \leq STP_t < 12$		
16		$12 \leq VSP_t$	$12 \leq STP_t$		
21	Coast	$VSP < 0$	$STP < 0$	$25 \leq v_t < 50$	
22	Cruise/ Acceleration	$0 \leq VSP_t < 3$	$0 \leq STP_t < 3$		
23		$3 \leq VSP_t < 6$	$3 \leq STP_t < 6$		
24		$6 \leq VSP_t < 9$	$6 \leq STP_t < 9$		
25		$9 \leq VSP_t < 12$	$9 \leq STP_t < 12$		
27		$12 \leq VSP_t < 18$	$12 \leq STP_t < 18$		
28		$18 \leq VSP_t < 24$	$18 \leq STP_t < 24$		
29		$24 \leq VSP_t < 30$	$24 \leq STP_t < 30$		
30		$30 \leq VSP_t$	$30 \leq STP_t$		
33	Cruise/ Acceleration	$VSP < 6$	$STP < 6$	$50 \leq v_t$	
35		$6 \leq VSP_t < 12$	$6 \leq STP_t < 12$		
37		$12 \leq VSP_t < 18$	$12 \leq STP_t < 18$		
38		$18 \leq VSP_t < 24$	$18 \leq STP_t < 24$		
39		$24 \leq VSP_t < 30$	$24 \leq STP_t < 30$		
40		$30 \leq VSP_t$	$30 \leq STP_t$		

Source: Reference (EPA, 2015a)

[1] VSP applies to light duty vehicles

[2] STP applies to heavy duty vehicles

Where,

CE_c	=	cycle average energy use rate (Kilojoules/mile) or emission rate (g/mile) for any arbitrary driving cycle c, for a fleet of vehicles with mixed types and ages
$EF_{b,a,v}$	=	base energy use rate (Kilojoules/mile) or emission rate (g/mile) for base cycle b, age a, and vehicle type v
$CCF_{c,a,v}$	=	cycle correction factor for driving cycle c, age a, and vehicle type v
$f_{a,v}$	=	age fraction for age a and vehicle type v
f_v	=	vehicle type fraction for vehicle type v
c	=	user defined driving cycle c
v	=	MOVES Lite defined vehicle types (see Table 1 for definitions)
a	=	vehicle age
b	=	base cycle

The cycle correction factor (CCF) for a given cycle, vehicle type, and vehicle age is the ratio of the energy use or emission rate for any cycle to that of the base cycle:

$$CCF_{c,a,v} = \left(\frac{(\sum_m f_{t,m}^{c} \times ER_{a,v,m})}{(\sum_m f_{t,m}^{b} \times ER_{a,v,m})} \right) \left(\frac{V^b}{V^c} \right) \quad (5)$$

Where,

$ER_{a,v,m}$	=	OpMode energy use or emission rate for age a, vehicle type v, in OpMode m; defined in section 4.1
$f_{t,m}^{c}$	=	fraction of time spent in OpMode m for cycle c
$f_{t,m}^{b}$	=	fraction of time spent in OpMode m for base cycle b
V^c	=	cycle average speed for cycle c (miles per hour, mph)
V^b	=	cycle average speed for base cycle b, mph
m	=	OpMode

2.4 CALIBRATING MOVES LITE: EFFECTIVE OPMODE RATES

MOVES default database includes OpMode energy use and emission rates in kilojoules/hour (kJ/hr) in a data table '**EmissionRates'**. The rates are given for each combination of a given fuel type, engine technology, regulatory class, and model year. However, while estimating cycle average energy use and emission rates for a given vehicle type, age, ambient condition, and cycle, MOVES accounts for internal adjustments of the default OpMode rates such as for location and fuel effects (EPA, 2015c). Thus, to account for any internal adjustments of the default OpMode rates, an approach was used to extract the OpMode energy use and emission rates actually used by MOVES. These rates are referred to as effective OpMode rates.

To extract the effective OpMode rates from MOVES, the approach is to run MOVES at the baseline ambient condition (67 ^{o}F temperature and 77% humidity) for each vehicle type, for each of 31 ages, corresponding to each of the 23 OpModes on a one hour basis. The approach for developing the effective OpMode energy use and emission rates includes the following steps:

(1) Running the MOVES2014a in a Project Domain/Scale;

(2) For Time Spans, set the calendar Year as 2015, Months as July, Days as Weekdays, Hours as 17:00 – 17:59;
(3) For the Geographic Bounds, set to a location of interest (e.g., District of Columbia);
(4) For On Road Vehicle Equipment, select one of the default vehicle types, as shown in Table 1, for each model run;
(5) For Road Type, select Urban Restricted Access;
(6) For Pollutants and Processes, select Total Energy Consumption or Emission Ratefor Running Exhaust.
(7) For the General Output, select the energy units as KiloJoules, and distance units as Miles, and for pollutants select a mass per distance unit;
(8) In the MOVES Project Data Manager, for each selected vehicle type:
    a. For Meteorology Data, set up temperature as 67 ^{o}F and relative humidity as 77%, which is the baseline ambient condition;
    b. For I&M (inspection and maintenance) Programs, only passenger cars and passenger trucks have either I&M or non I&M programs. I&M programs are not applicable to heavy duty vehicles. Therefore, for SHT and LHT, effective OpMode rates are selected only for the non I&M program scenario;
    c. For Operating Mode Distribution, set the OpMode faction as 1 for each OpMode bin for each model run;
    d. For Age Distribution, set the age fraction as 1 for each age for each model run;
    e. For Links, set link length as 1 mile, link average speed as 1 mph, and link volume as 1 vehicle per hour. This setting assure the effective OpMode energy use or emission rate, reported from the MOVES output, represents the hourly amount of energy use or emissions for one single vehicle;
    f. For Link Source Types, set hour fraction of the source type as 1.

These effective OpMode rates were used in MOVES Lite to estimate the cycle correction factors, as shown in Equation (5), which in turn were used in estimating the cycle average energy use and emission rates.

2.5 CALIBRATING MOVES LITE: BASE RATES

MOVES2014a was run to estimate the hot stabilized base energy use and emission rates on a per distance basis. The selected geographic region is Washington DC, and the base driving cycle is Federal Test Procedure (FTP). The FTP cycle has three bags of emission measurements. Bag 1 and bag 3 have the same speed-time traces. Bag 1 is measured upon a vehicle cold start. Bag 3 is measured beginning with a hot start (EPA, 2001). The entire cycle is 1875 seconds including the three bags, and an average speed of 21.2 miles per hour. The FTP cycle is one of the most important driving cycles used for vehicle emission certification tests and compliance to emission standards (40 CFR 86.1811-04). Thus, FTP is selected as the base cycle. The OpMode distributions for FTP cycle were estimated for each vehicle type and were input into MOVES for estimating base rates. The model results are not sensitive to the choice of base cycle. The base cycle is merely used as a calibration basis for the cycle correction factor.

The default OpMode rates in MOVES represent a single baseline scenario of ambient temperature, relative humidity, and default fuel properties including sulfur, oxygenate, ethanol, olefin, aromatic, vapor pressure, and distillation properties. MOVES was run for baseline ambient conditions at a temperature of 67^{o}F and relative humidity of 77%. The base energy use and emission rates were obtained for each vehicle age from 0 year to 30 years.

2.6 MOVES LITE INPUTS

MOVES Lite was developed and tested using MATLAB R2017a. There are two kinds of inputs to MOVES Lite: user specified inputs, and default model inputs. The MOVES Lite Phase I model had three user-specified input variables: (i) second-by-second driving cycle, including speed and road grade, (ii) for type distribution, and (iii) vehicle age distribution. These user inputs are read by the program through MS Excel files, where the files can have extensions of ".xls", ".xlsx", and ".csv". The three input files can have any name. Thus, MOVES Lite is able to read any excel file extension saved with any name. User inputs could be from another software, such as DTAlite.

Table 6 lists the key user specified inputs of the updated MOVES Lite. The column 'Input excel files' shows the category of each required input from the user. The files can be saved with any name. The column 'User input' shows the variable for which user input is needed. In the first input file, the user has to enter driving cycle data including: cycle ID such as 1, 2, and 3 for three different driving cycles; and second-by-second speed (miles per hour) and road grades (in fraction) for each of the driving cycles. The second input file includes rows for each vehicle type, and associated fractions within the entire fleet.

The third input file is for the age distribution from 0 to 30 years of age for each of the vehicle types. For example, if only a zero year old SHT has to be selected, user will enter 1.0 for the age fraction column in the row for zero (0) year, and the rows for other ages for SHT will be zero.

Table 6: Key user specified inputs in MOVES Lite

Input excel files*	User input	Symbol
Driving cycle	Cycle ID	c
	Time (seconds)	t
	Speed (miles per hour)	v_t
	Road grade (fraction)	r_t
Vehicle type	Vehicle type fraction (fraction of traffic volume based on source type, regulatory class, and fuel type)	v
Vehicle age	Age fraction (for 0 to 30 years for each vehicle type)	a

* the excel files can be saved with any name and can have extensions of ".xls", ".xlsx", and ".csv"

For integration with the traffic simulation model, DTA-Lite version passes relevant outputs as inputs to MOVES Lite. In DTA-Lite, 'vehicle attribute' data is generated using road link (i.e. road segment) and node (i.e. road intersection) network data, vehicle type fraction, and age fraction (EPA, 2006). These three DTA-Lite parameters regarding vehicle type are passed to MOVES Lite. The other three inputs are associated with driving cycle, including the second-by-second time, speed and acceleration profile that comes from the microscopic vehicle trajectory simulation.

MOVES Lite has five default calibrated parameters: (i) effective OpMode energy use and emission rates for each vehicle type and age; (ii) base energy use and emission rates; (iii) OpMode (VSP, and STP) parameters for each vehicle type; (iv) OpMode definition; and (v) OpMode time distribution for each vehicle type for the base driving cycle.

2.7 MOVES LITE OUTPUTS

MOVES Lite estimates cycle average and fleet average energy use (kJ/mile) and emission (g/mile) rates CO_2 emission rates are inferred as a function of cycle average energy use rate as per a MOVES2014a formula (EPA, 2015d):

$$CE_{CO2,c} = OF \times \left(\frac{44}{12}\right) \times \sum_{v}(CE_{c,v,energy} \times cc_{F,v}) \quad (6)$$

Where,

$CE_{CO2,c}$	=	cycle average CO_2 emission rate (grams/mile) for a driving cycle c for a fleet of mixed vehicle types and ages
$CE_{c,v,energy}$	=	cycle average energy use rate (kJ/mile) for a driving cycle c, vehicle type v
$cc_{F,v}$	=	carbon content (grams of carbon/kJ of energy) for a fuel type f of a vehicle type v. For diesel, cc = 0.0202 (EPA, 2015d)
OF	=	oxidation fraction which is the carbon fraction in fuel oxidized to form CO_2 in the atmosphere. OF is assumed to be 1 in MOVES (EPA, 2015d).

2.8 VERIFICATION

MOVES Lite Phas been verified based on comparisons to MOVES estimates for selected driving cycles. For SHT, MOVES has 13 default cycles with average speed from 1.8 mph to 77.8 mph. For LHT, there are 13 default cycles with average speed ranging from 1.8 mph to 76.7 mph. The cycle data are contained in MOVES default data tables **‘DriveScheduleAssoc’** and **‘DriveScheduleSecond’**. MOVES uses these cycles to estimate emission rates when a user enters a link average speed in the project level analysis mode. Thus, these cycles are a convenient basis for comparisons of MOVES Lite to MOVES.

Differences between the estimated energy use and emission rates from the MOVES Lite and MOVES have been expressed as a percentage error compared to MOVES energy and emissions estimates, which quantify MOVES Lite ability to predict MOVES estimates:

$$e = \frac{(\text{MOVES Lite} - \text{MOVES})}{\text{MOVES}} \times 100 \quad (7)$$

Where, e is the % error in MOVES Lite estimates.

Verification was done for the vehicle types defined in Table 1, each for vehicle ages of 0, 5, 7, 9, 10, 15, and 30 years based on calendar year 2015. MOVES and MOVES Lite were individually run for each vehicle type, associated driving cycles (i.e. all 13 cycles for SHT, and all 13 cycles for LHT), and age distribution (i.e. for 0, 5, 7, 9, 10, 15, and 30 years old vehicles) each for baseline ambient conditions, and fuel properties for Washington DC. SHT and LHT, are not subject to I&M programs and, thus, the non-I&M rates were used for these heavy duty vehicles.

3.0 RESULTS

Results include extraction of effective operating mode rates from MOVES, estimation of base rates using MOVES, quantification of default driving cycles, estimation of cycle average rates for the default driving cycles, and verification of MOVES light in comparison to MOVES.

3.1 EFFECTIVE OPERATING MODE RATES

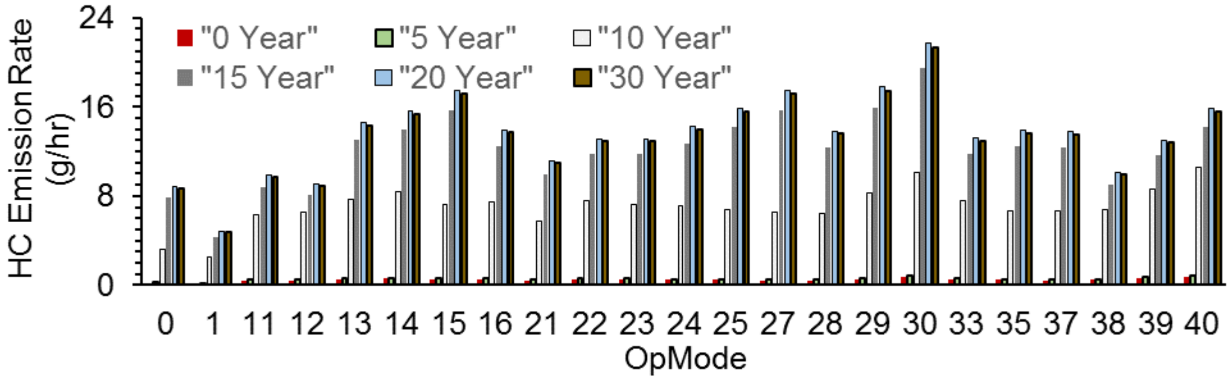
Effective operating mode rates were obtained from MOVES for short-haul and long-haul trucks of ages 0, 5, 7, 9, 10, 15, and 30 years old, based on calendar year 2015. These ages were selected because they represent periods of different emission standards. For examples, vehicles five years old and newer in calendar year 2015 include model years 2010 to 2015, which are all subject to the same standard. Model years 2007 to 2009 were subject to a different standard, and so on.

Effective opmode rates for short-haul trucks ages 0, 5, 10, 15, 20, and 30 years old are shown in Figure 1 for hydrocarbon (HC), CO, NO_x, and $PM_{2.5}$ emission rates and for energy use rates. Results are not shown separately for CO_2 emission rates because CO_2 emission rates are proportional to energy use rates.

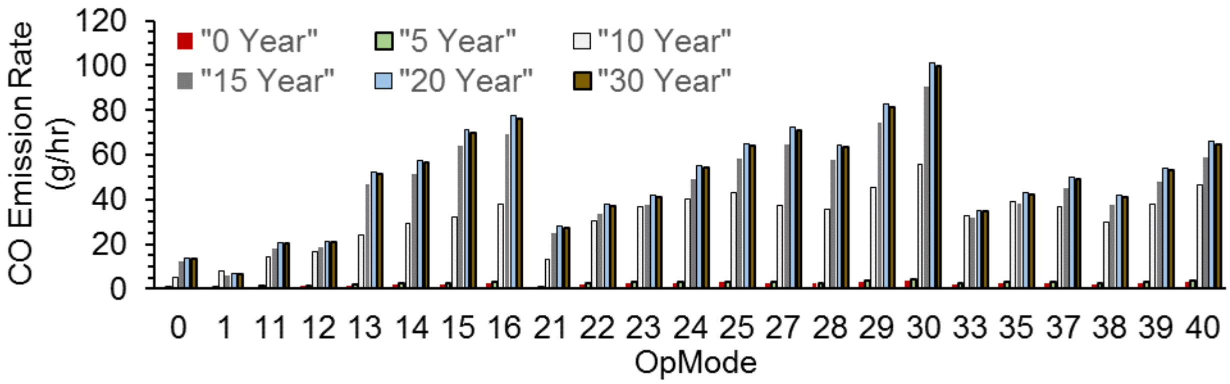
As shown in Table 5, OpMode 0 includes deceleration and braking, and OpMode 1 includes idling. For a given pollutant and for energy use, the OpMode 1 rates are lower than all other OpMode rates. OpMode 0 rates tend to be higher than OpMode 1 rates because the engine is often running at elevated revolutions per minute (RPM) during deceleration or braking, whereas the engine is typically running at idle RPM during idling. Idle RPM is the lowest RPM at which the engine is set to run. Thus, the mass air flow rate through the engine is lower, on average, for idle than for deceleration or braking. The fuel use and emission rates also are typically lower.

Typically, the OpMode average rate increases with increasing positive STP within each speed range. For example, NOx emission rates increase from OpModes 11 to 16 within the 1 mph to 25 mph speed range, from OpModes 21 to 30 within the 26 mph to 50 mph speed range, and from OpModes 33 to 40 within the 51 mph and greater speed range.

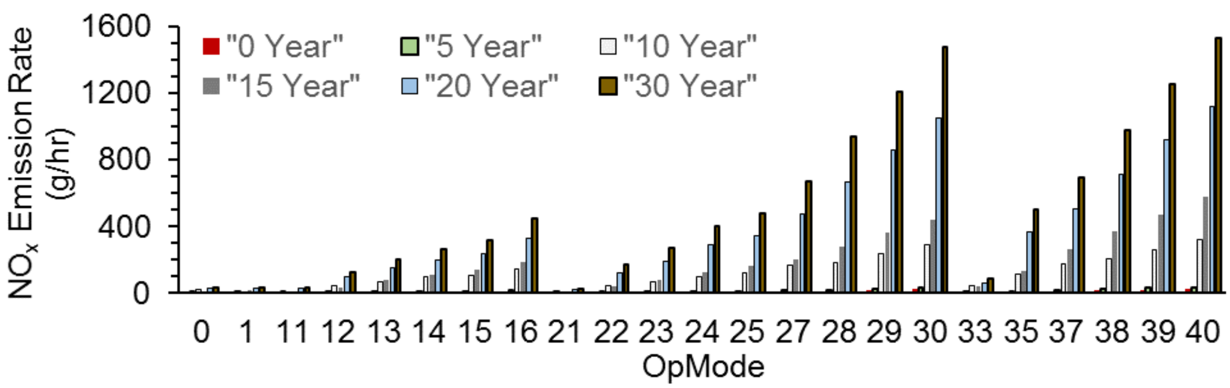
For air pollutant emission rates, the effective OpMode rates are the lowest for the newest (age 0 vehicles) in calendar year 2015, and typically increase with age. For example, emission rates for 0 year old vehicles are only 3.6%, 4.6%, 2.2%, and 0.10% of the rates for 30 year old vehicles for HC, CO, NO_x, and $PM_{2.5}$, respectively. These substantial reductions in emission rates over time are the result of increasingly stringent emission standards for heavy duty diesel vehicles. The most recent standard, implemented in 2010, is typically met with a combination of exhaust gas recirculation (EGR), diesel oxidation catalyst (DOC), diesel particle filter (DPF), and selective catalytic reduction (SCR) (Sandhu and Frey, 2012). EGR and SCR are used for NO_x control. DOC is effective at reducing emission rates of HC and CO. DPF is effective at reducing $PM_{2.5}$ emission rates.



(a) Hydrocarbon Emission Rates

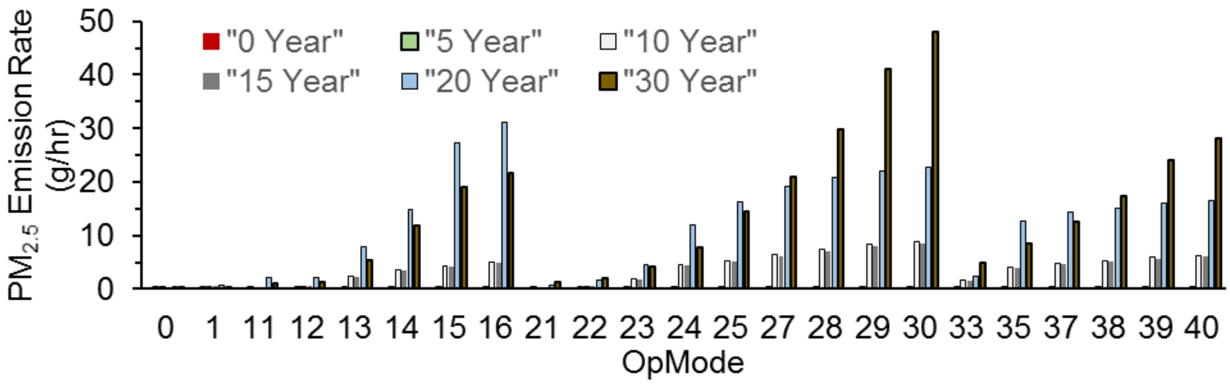


(b) Carbon Monoxide Emission Rates

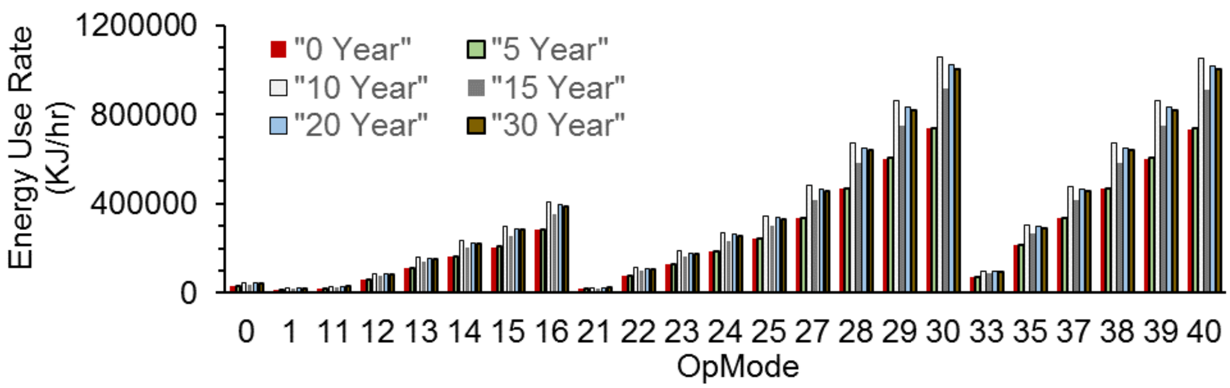


(c) Nitrogen Oxides Emission Rates

Figure 1. Effective OpMode Emission and Energy Use Rates for Short Haul Trucks of Selected Ages (Continued on Next Page).



(d) Fine Particulate Matter ($PM_{2.5}$) Emission Rates



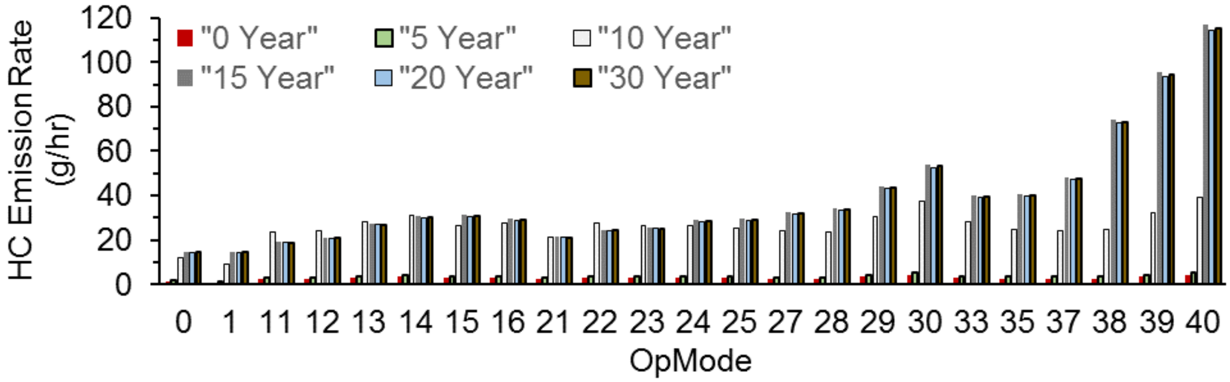
(e) Energy Use Rates

Figure 1. Effective OpMode Emission and Energy Use Rates for Short Haul Trucks of Selected Ages

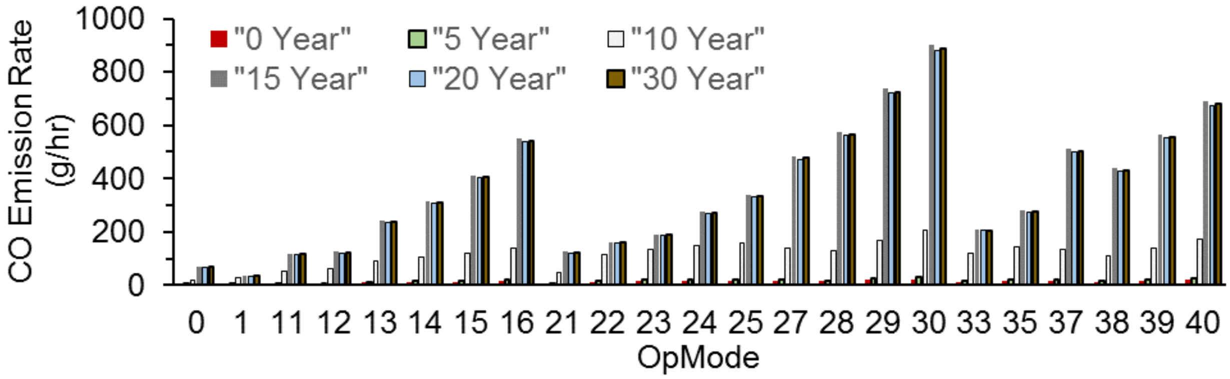
Energy use rates have a different trend with respect to age than do emission rates. There is much less variability in energy use rates from one age to another within a given OpMode than there is for the emission rates of a given pollutant. Energy use rates are primarily related to vehicle weight, but are affected by improvements in vehicle aerodynamics, reductions in auxiliary loads, and reductions in rolling resistance. In recent years, EPA has demonstrated the use of more efficient truck technologies as part of its “Smartway” program. These energy efficiency reductions lead to fuel cost savings, which can be quite significant for freight trucks that accumulated a large number of miles in a given year. Some implementations of emission controls, such as EGR, have led to some efficiency penalties. However, in recent years, the use of post-combustion emission controls such as DPF and SCR has enabled achievement of deep reductions in $PM_{2.5}$ and NO_x emission rates, respectively. Because these emission control technologies have high emission control efficiencies, it is possible to optimize the engine for better energy efficiency almost irrespective of whether engine-out emissions might increase. Thus, the newest model year vehicles with the most stringent emission controls also tend to be the most energy efficient vehicles.

The effective OpMode rates for Long Haul Trucks are given in Figure 2. The relative trends in LHT OpMode rates are approximately similar to those for SHT. For example, the lowest OpMode rates are at idle, and typically increase monotonically with increasing STP within a speed range. The emission rates for 0 year old LHT average 9.0%, 4.5%, 3.2%, and 0.17% of those for 30 year old trucks for HC, CO, NO_x, and $PM_{2.5}$, respectively. The average energy use rates for 0 year old trucks are only 3.9% lower than for 30 year old trucks, however. LHT trucks are typically the largest, heaviest trucks for which truck weight is a key factor in total energy use.

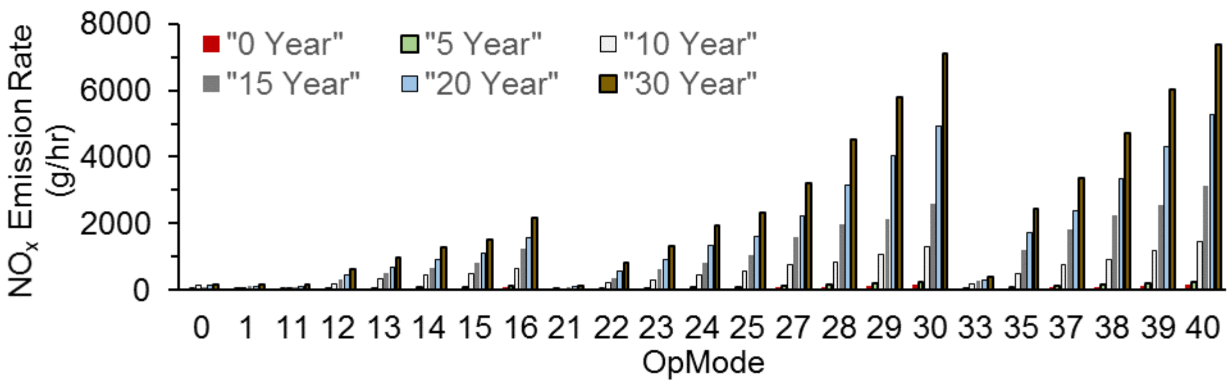
The effective OpMode rates in Figures 1 and 2 for SHT and LHT, respectively, are used as input to Equation (5) to calculate the cycle correction factor in MOVES Lite.



(a) Hydrocarbon Emission Rates

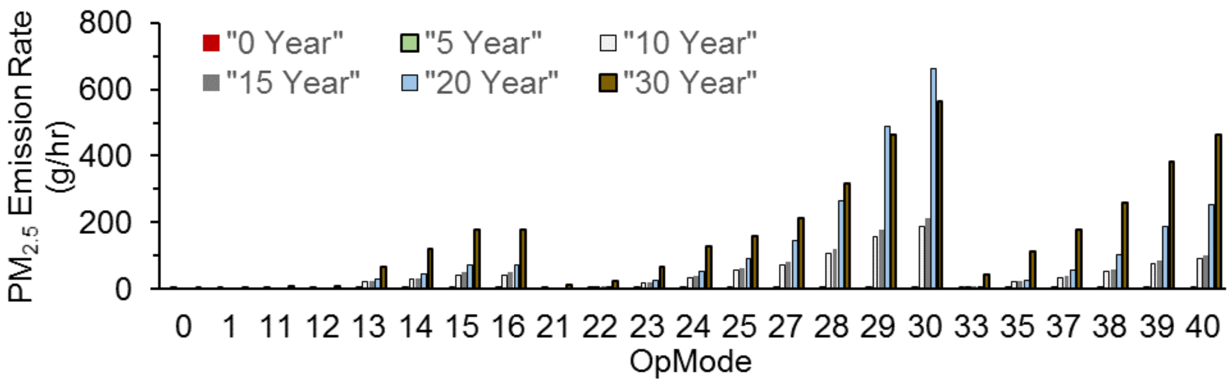


(b) Carbon Monoxide Emission Rates

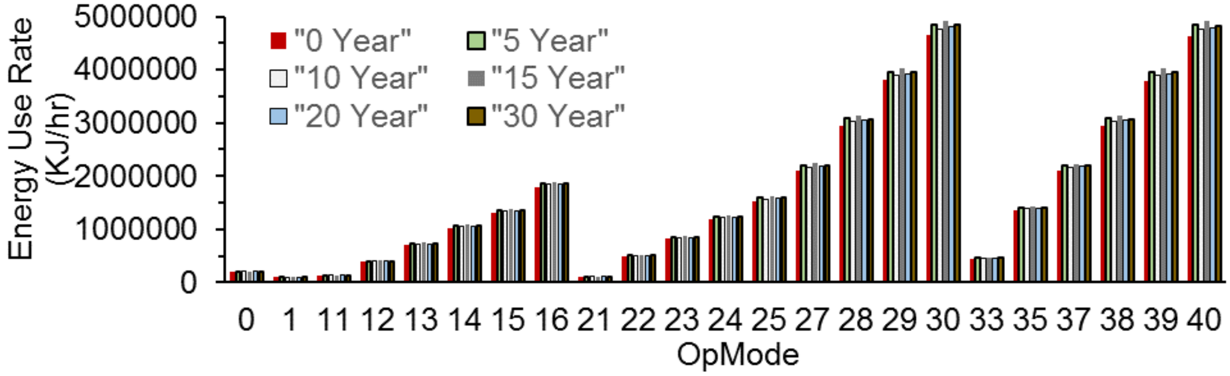


(c) Nitrogen Oxides Emission Rates

Figure 2. Effective OpMode Emission and Energy Use Rates for Long Haul Trucks of Selected Ages (Continued on Next Page).



(d) Fine Particulate Matter ($PM_{2.5}$) Emission Rates



(e) Energy Use Rates

Figure 2. Effective OpMode Emission and Energy Use Rates for Long Haul Trucks of Selected Ages

3.2 BASE RATES

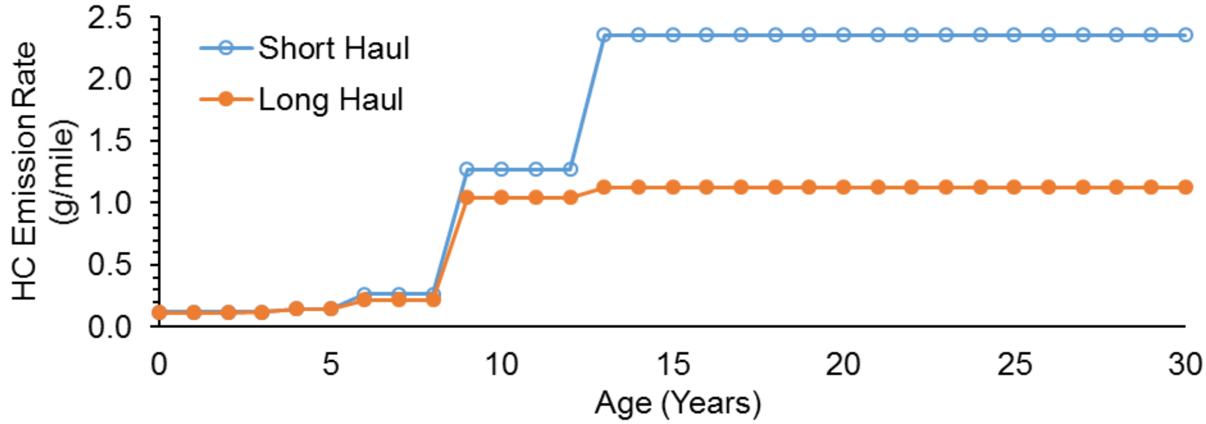
Base emission and energy use rates are used in MOVES Lite as a basis for calibrating MOVES Lite to MOVES. The base rates are a key input to Equation (4) of MOVES Lite.

The base rates for SHT and LHT are shown in Figure 3 for HC, CO, NO_x, $PM_{2.5}$, and energy use. These rates are based on the Federal Test Procedure (FTP) cycle. Although the FTP cycle is used for regulatory purposes for light duty vehicles, it can be used as an input to MOVES for any vehicle type. Base rates for CO_2 are not shown because CO_2 emission rates are estimated based on energy use rates. Thus, the relative trends in CO_2 emission and energy use rates are the same.

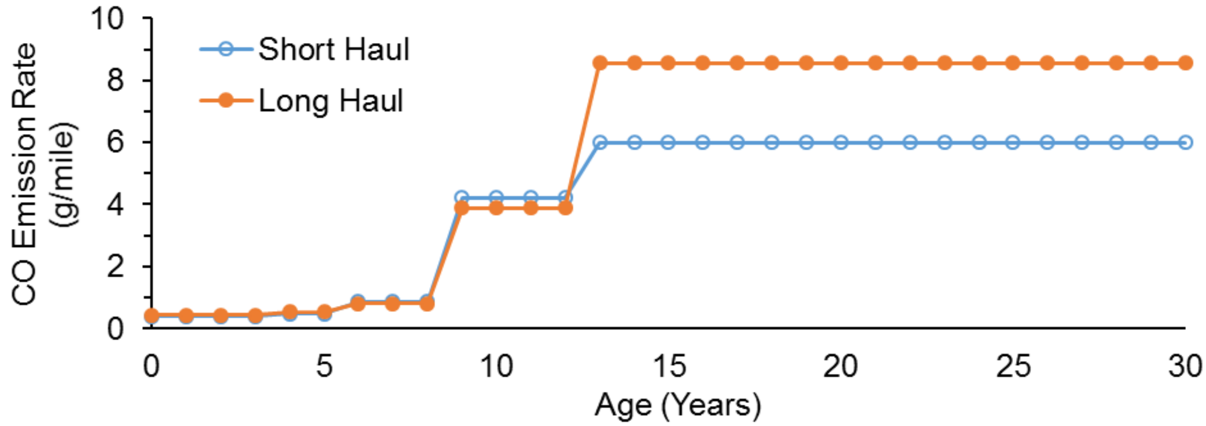
For HC, NO_x, and CO, the MOVES estimates of base emission rates are shown to typically decrease with decreasing age in a step-wise manner for both SHT and LHT. These step decreases in emission rates are associated with the implementation of successively more stringent vehicle emission standards. For example, the currently in-place emission standards have been in effect since the 2010 model year, corresponding to vehicles of ages 5 or newer compared to the calendar 2015 base year. The prior change in standard took place in 2007, corresponding to vehicles of 6 to 8 years of age in calendar year 2015, and so on.

$PM_{2.5}$ emission rates typically decrease from older to newer vehicles, although there was a period of time in which a trade-off between $PM_{2.5}$ emissions and emissions of other pollutants was made in favor of reducing emissions of the other pollutants, such as NO_x.

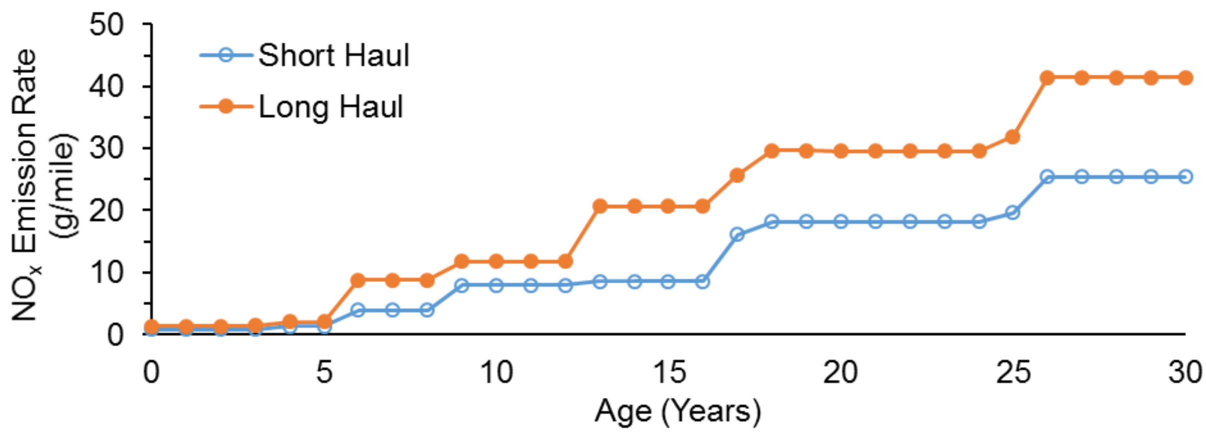
Typically, LHT have higher emission rates than SHT for CO, NO_x, and $PM_{2.5}$. However, as emission standards have become more stringent over time, the absolute difference in emission rates between LHT and SHT has decreased. Furthermore, the emission rates for 0 year old vehicles are far lower than for 30 year old vehicles. For HC emission rates, older SHT have higher emission rates than LHT, according to MOVES, but the rates are approximately similar for both types of trucks in recent model years. Energy use rates are consistently higher for the larger, heavier LHT versus SHT.



(a) Hydrocarbon Emission Rates

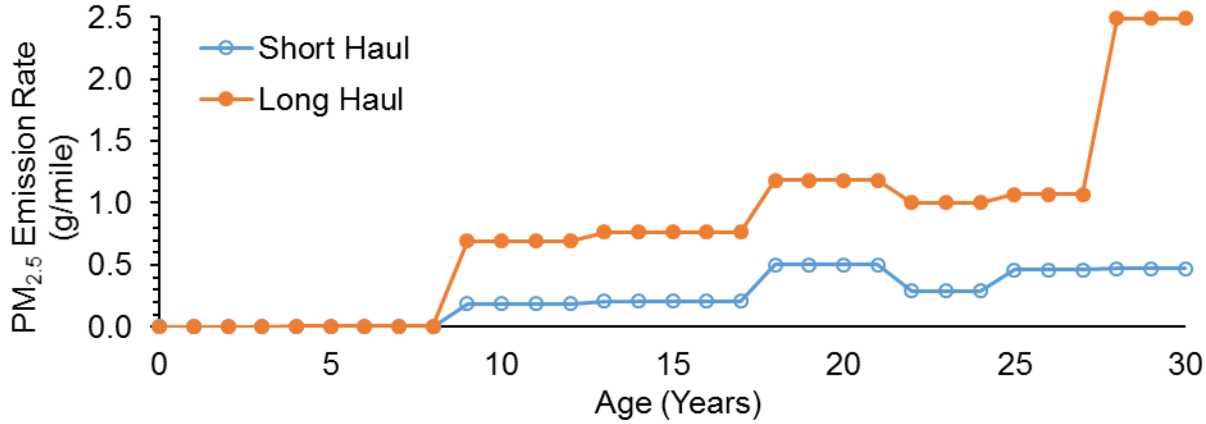


(b) Carbon Monoxide Emission Rates

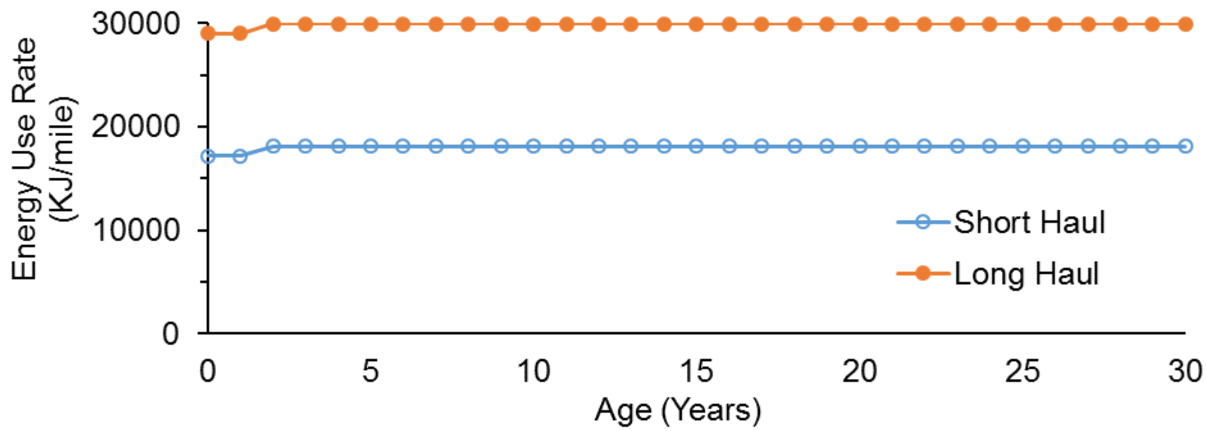


(c) Nitrogen Oxides Emission Rates

Figure 3. Base Emission and Energy Use Rates for Short Haul Trucks and Long Haul Trucks for Ages 0 to 30 Years (continued on next page).



(d) Fine Particulate Matter ($PM_{2.5}$) Emission Rates



(e) Energy Use Rates

Figure 3. Base Emission and Energy Use Rates for Short Haul Trucks and Long Haul Trucks for Ages 0 to 30 Years.

3.3 DEFAULT DRIVING CYCLES

MOVES includes 13 default driving cycles for SHTs and 13 default driving cycles for LHTs. The LHT default cycles are, in most cases, different than those for SHT. Table 7 summarizes the default driving cycles for SHTs and Table 8 summarizes the default driving cycles for LHTs. Second-by-second speed traces for each cycle are given in the Appendix.

MOVES Cycle 398, with an average speed of 1.77 miles/hour, is used as a default cycle for both SHT and LHT in the MOVES model. However, the remaining default cycles are different for LHT versus SHT. The range of average speeds for the default cycles are similar for the two vehicle types, ranging from 1.77 mph to 77.8 mph for SHT and from 1.77 mph to 76.7 mph for LHT. However, the range of cycle average STP is different, ranging from 0.0.4 skW/Mt to 5.21 skW/Mt for SHT and 0.10 skW/Mt to 11.64 skW/Mt for LHT.

Some of the default cycles start and end with zero speed, such as Cycle 201, while others are partial segments of a longer trip, such as Cycle 397. The cycles with average speeds over 70 mph have very little variability in speed and no stops, whereas cycles with average speeds of 35 mph or lower typically include one or more stops.

The distribution of time for each cycle among the OpModes is given in Table 9 for SHT and Table 10 for LHT. The cycles with the lowest average speeds, including Cycles 398, 201, and 301, have no time at speeds greater than 25 mph. In contrast, for cycles such as 255, 354, 355, 396, and 397, which have high average speeds, have little to no time at speeds of 50 mph or less.

Although the speed profiles are not very different between the SHT and LHT default cycles, the cycle average STP tends to be higher for LHT. This is because the rolling resistance coefficient, rotating resistance coefficient, drag coefficient, and source mass factor are greater for LHT than for SHT, as given in Table 4. Thus, for a given speed and acceleration, STP tends to be greater for LHT than for SHT. The distribution of time in each mode tends to be shifted toward higher STP modes in Table 10 than for Table 9.

Table 7. Default Driving Cycles and Base Cycle (FTP) for Short-Haul Trucks, Sorted by Cycle Average Speed

Cycle ID	Name of cycle	Average Speed (mph)	Time duration (seconds)	Distance (miles)	Average STP (kW/Mt)
13	Cycle398	1.77	253	0.12	0.04
1	Cycle201	4.6	293	0.37	0.14
2	Cycle202	10.7	311	0.93	0.33
3	Cycle203	15.6	454	1.97	0.44
4	Cycle204	20.8	1046	6.05	0.59
0	FTP	21.2	1876	11.10	0.66
5	Cycle205	24.5	566	3.85	0.72
6	Cycle206	31.5	988	8.64	1.06
7	Cycle251	34.4	1637	15.63	1.15
8	Cycle252	44.5	3504	43.33	1.77
9	Cycle253	55.4	2718	41.85	2.49
10	Cycle254	60.1	4866	81.30	2.86
11	Cycle255	72.8	4782	96.72	4.41
12	Cycle397	77.8	4782	103.36	5.21

Table 8. Default Driving Cycles and Base Cycle (FTP) for Long-Haul Trucks, Sorted by Cycle Average Speed

Cycle ID	Name of cycle	Average Speed (mph)	Time duration (seconds)	Distance (miles)	Average STP (kW/Mt)
13	Cycle398	1.77	253	0.12	0.10
1	Cycle301	5.8	260	0.42	0.43
2	Cycle302	11.2	608	1.89	0.72
3	Cycle303	15.64	567	2.46	1.15
4	Cycle304	19.4	558	3.01	1.32
0	FTP	21.2	1876	11.10	1.62
5	Cycle305	25.6	983	7.00	1.82
6	Cycle306	32.5	809	7.30	2.94
7	Cycle351	34.3	2276	21.66	2.73
8	Cycle352	47.12	3197	41.85	4.29
9	Cycle353	54.2	5333	80.27	5.40
10	Cycle354	59.7	1792	29.71	6.41
11	Cycle355	71.7	1792	35.68	9.86
12	Cycle396	76.7	1792	38.17	11.64

Table 9. Distribution of Operating Modes by Fraction of Time for Default and Base (FTP) Cycles for Short-Haul Trucks

Op-Modes	Fraction of time in Each OpMode by Cycle ID													
	FTP	201	202	203	204	205	206	251	252	253	254	255	397	398
0	0.13	0.04	0.10	0.13	0.11	0.12	0.13	0.07	0.03	0.02	0.01	0.01	0.01	0.02
1	0.19	0.31	0.22	0.13	0.09	0.11	0.06	0.00						0.44
11	0.06	0.27	0.23	0.17	0.11	0.07	0.05	0.10	0.04	0.01	0.00			0.05
12	0.15	0.35	0.30	0.28	0.19	0.12	0.08	0.17	0.07	0.02	0.01			0.49
13	0.06	0.03	0.07	0.06	0.07	0.05	0.04	0.02	0.01	0.00	0.00			
14	0.01		0.01	0.01	0.00	0.00	0.01	0.00	0.00					
15				0.00	0.00	0.00	0.00							
16			0.00				0.00							
21	0.07		0.01	0.06	0.13	0.12	0.12	0.11	0.08	0.02	0.01	0.00		
22	0.20		0.04	0.11	0.17	0.25	0.23	0.19	0.19	0.04	0.01			
23	0.04		0.01	0.06	0.10	0.14	0.13	0.11	0.09	0.04	0.01			
24	0.01		0.01	0.01	0.02	0.01	0.06	0.03	0.02	0.01	0.00			
25	0.00				0.00	0.00	0.01	0.01	0.00	0.00	0.00			
27					0.00		0.00		0.00	0.00				
28									0.00					
29														
30								0.00	0.00					
33	0.08						0.08	0.17	0.42	0.78	0.87	0.74	0.61	
35	0.00						0.01	0.01	0.04	0.07	0.07	0.22	0.34	
37							0.00	0.00	0.01	0.01	0.01	0.02	0.03	
38									0.00	0.00	0.00	0.01	0.01	
39									0.00		0.00	0.00	0.00	
40										0.00		0.00	0.00	

NOTE: Values of "0.00" are greater than 0 but less than 0.005. Blank cells represent 0 time fractions.

Table 10. Distribution of Operating Modes by Fraction of Time for Default and Base (FTP) Cycles for Long-Haul Trucks

Op-Modes	Fraction of time in Each OpMode by Cycle ID													
	FTP	301	302	303	304	305	306	351	352	353	354	355	396	398
0	0.13	0.05	0.08	0.11	0.11	0.1	0.09	0.06	0.03	0.01	0.00	0.00	0.00	0.02
1	0.19	0.15	0.11	0.14	0.15	0.05	0.05							0.44
11	0.06	0.32	0.24	0.15	0.08	0.07	0.03	0.07	0.01	0.01				0.06
12	0.07	0.4	0.34	0.2	0.12	0.08	0.06	0.11	0.02					0.47
13	0.04	0.05	0.09	0.1	0.09	0.05	0.03	0.04	0.01					0.01
14	0.05	0.02	0.03	0.06	0.04	0.04	0.03	0.02	0.01					
15	0.03	0	0.02	0.01	0.01	0.02	0.01	0.01						
16	0.04	0.01	0.01	0.03	0.01	0.02	0.01	0.01						
21	0.08		0.04	0.05	0.08	0.15	0.16	0.11	0.1	0.03				
22	0.10		0.01	0.05	0.11	0.11	0.08	0.09	0.06	0.03				
23	0.07		0.01	0.05	0.07	0.11	0.11	0.09	0.07	0.03				
24	0.03		0.01	0.02	0.05	0.08	0.08	0.07	0.04	0.02				
25	0.01		0.01	0.01	0.03	0.05	0.07	0.06	0.04	0.01				
27	0.02			0.01	0.03	0.03	0.06	0.03	0.05	0.01				
28	0.01			0.01	0.01	0.01	0.02		0.01					
29				0.01		0.01	0.01							
30														
33	0.05						0.06	0.11	0.31	0.45	0.45	0.27	0.2	
35	0.02						0.02	0.06	0.14	0.29	0.4	0.38	0.33	
37	0.01						0.01	0.03	0.05	0.08	0.12	0.23	0.29	
38							0.01		0.02	0.02	0.03	0.09	0.12	
39									0.01	0.00	0.01	0.02	0.04	
40									0.01	0.01	0.01	0.01	0.02	

NOTE: Values of "0.00" are greater than 0 but less than 0.005. Blank cells represent 0 time fractions.

3.4 ESTIMATION OF CYCLE AVERAGE ENERGY USE AND EMISSION RATES

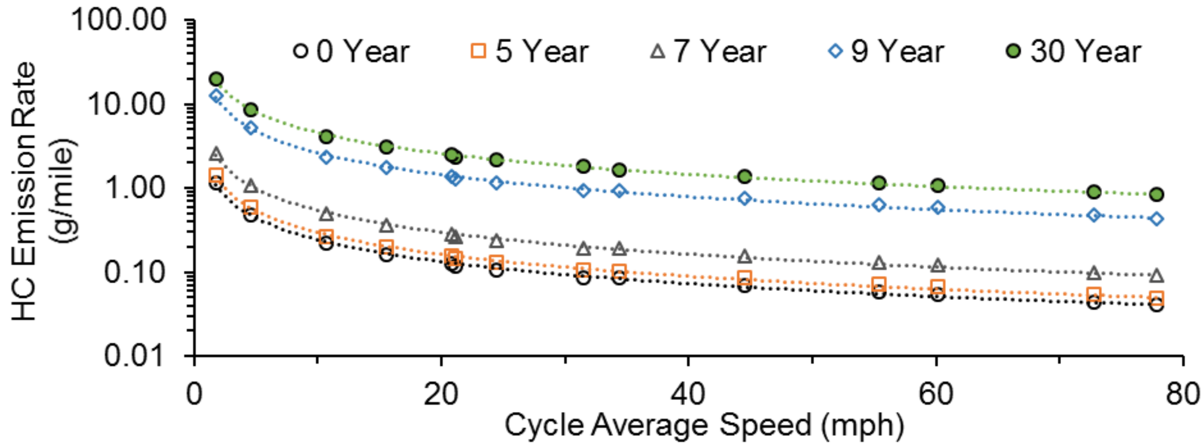
Using the MOVES Lite calibration data for base emission rates, effective OpMode rates, and fraction of time in each mode, as given in previous sections, cycle average rates are estimated for each default cycle using Equation (4). The results are given in Figure 4 for SHT and in Figure 5 for LHT.

Typically, the cycle average HC and CO emission rates decrease with increasing cycle average speed for both SHT and LHT and for every vehicle age. The variability in cycle average emission rate with respect to cycle average speed is approximately an order-of-magnitude or more for these pollutants. The cycle average emission rates are highest at the lowest cycle average speed. The cycle average rates for the oldest vehicles are more than an order-of-magnitude higher than those for the newest vehicles. Thus, both cycle average speed and vehicle age are important determinants of cycle average emission rates.

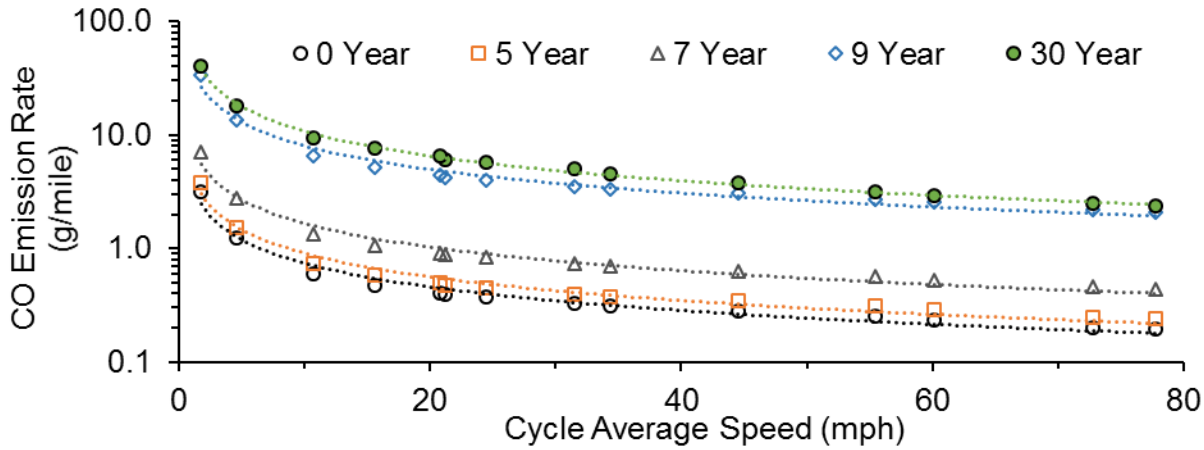
Cycle average NO_x emission rates are also highly variable with cycle average speed and with vehicle age. The relative differences in these rates are greater with respect to age than with respect to cycle average speed. The cycle average NO_x emission rates reach a minimum around 60 mph, and increase slightly with higher speeds that are greater than 60 mph.

Cycle average $PM_{2.5}$ emission rates are far more sensitive to vehicle age than to vehicle speed. These rates differ by more than three orders of magnitude when comparing 0 year old to 30 year old vehicles for a given cycle. The range of variability among driving cycles for a given age is less than an order-of-magnitude.

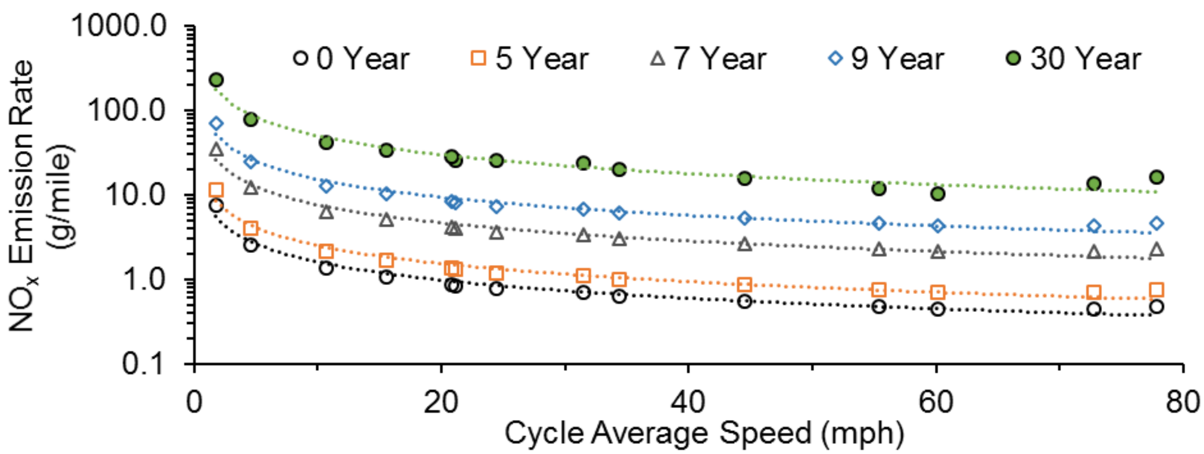
The trends in energy use rates and CO_2 emission rates are similar. For SHT, these rates vary by approximately an order-of-magnitude with respect to cycle average speed. The rates are very similar among all of the vehicle ages. The rates reach a minimum at approximately 60 mph, and increase with higher speeds. The trends are similar for LHT.



(a) Hydrocarbon Emission Rates

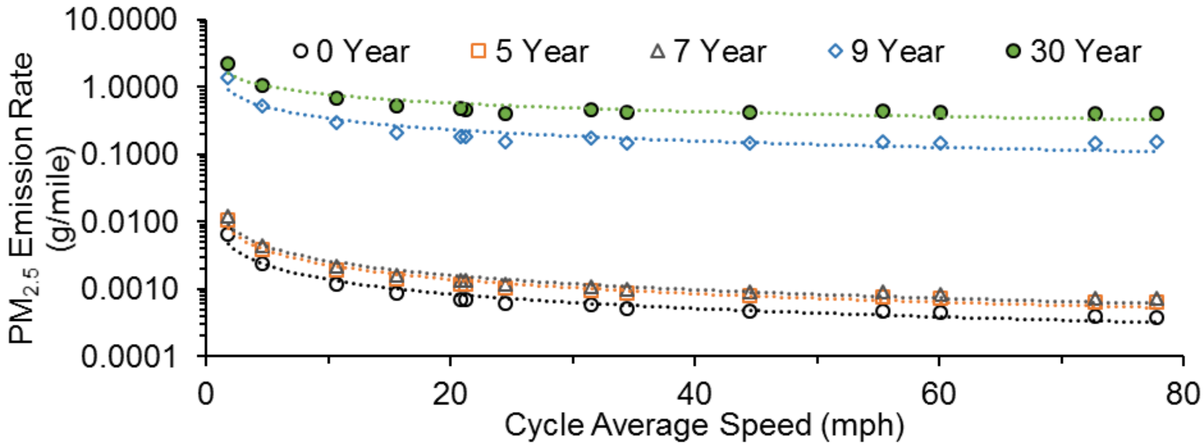


(b) Carbon Monoxide Emission Rates

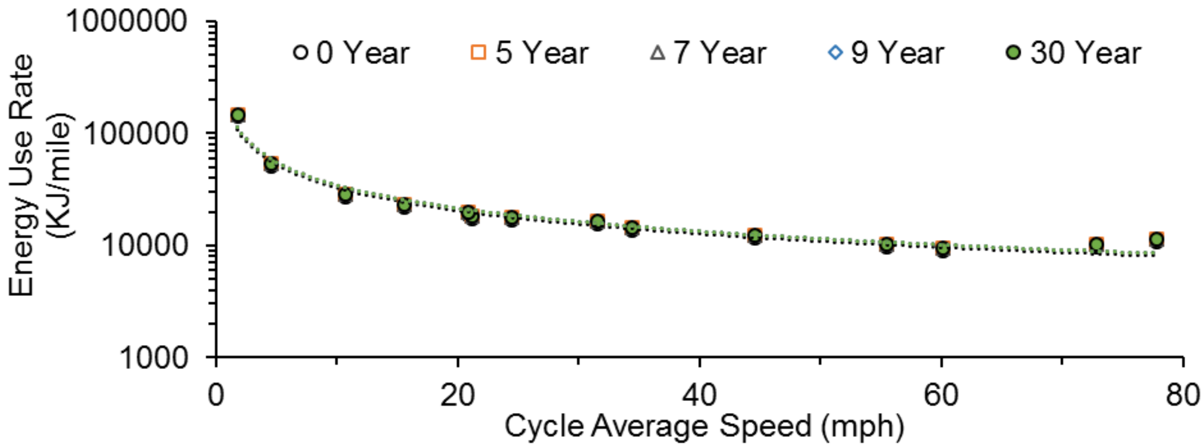


(c) Nitrogen Oxides Emission Rates

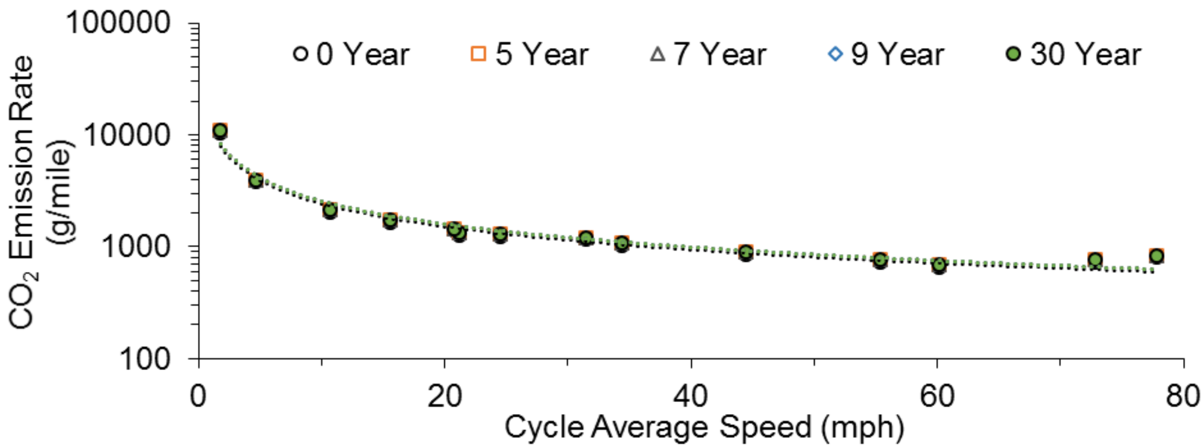
Figure 4. MOVES Cycle Average Emission and Energy Use Rates Versus Cycle Average Speed for Short-Haul Trucks (continued on next page)



(d) Fine Particulate Matter ($PM_{2.5}$) Emission Rates

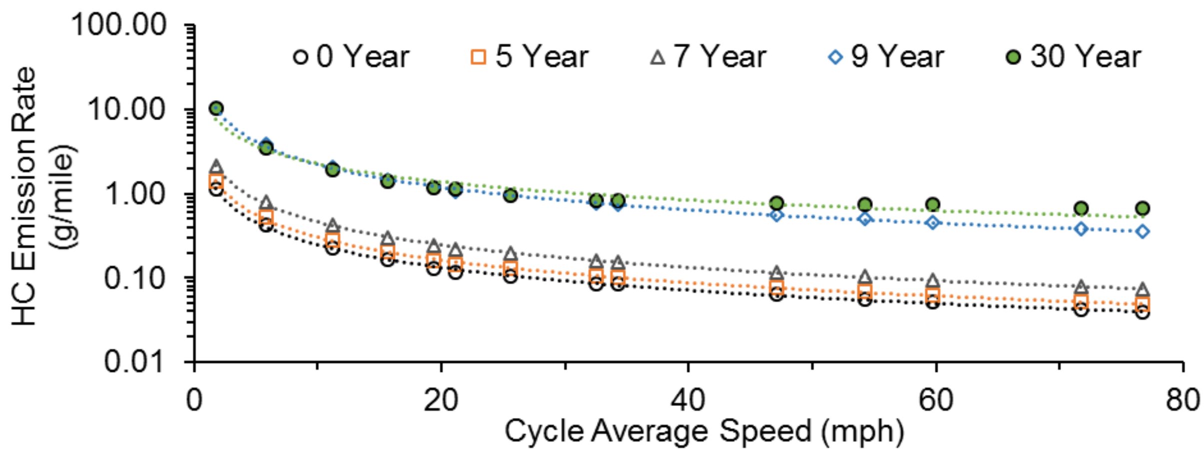


(e) Energy Use Rates

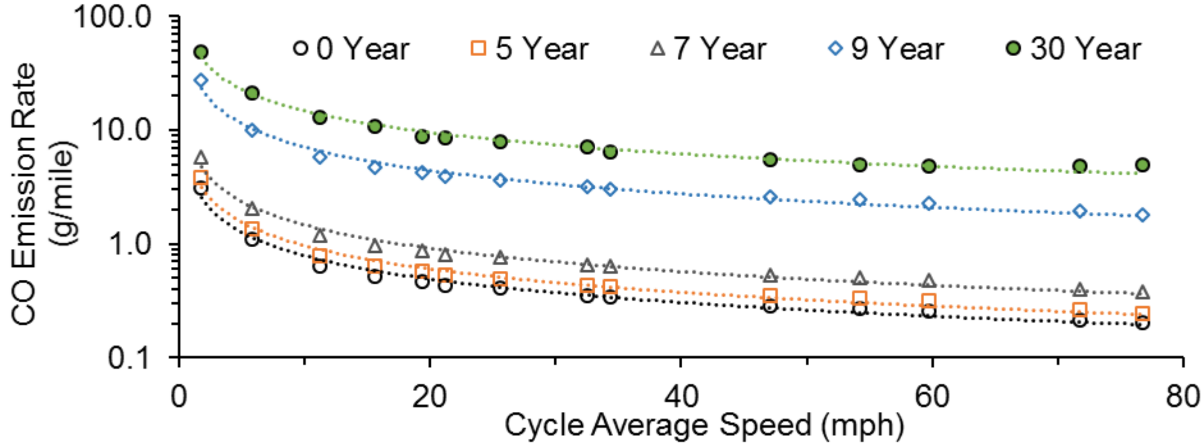


(f) Carbon Dioxide Rates

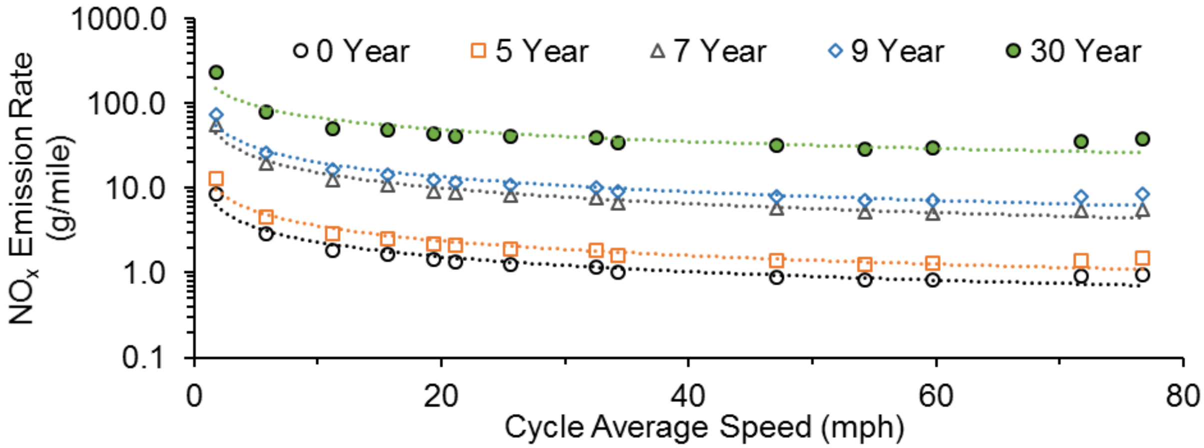
Figure 4. MOVES Cycle Average Emission and Energy Use Rates Versus Cycle Average Speed for Short-Haul Trucks.



(a) Hydrocarbon Emission Rates

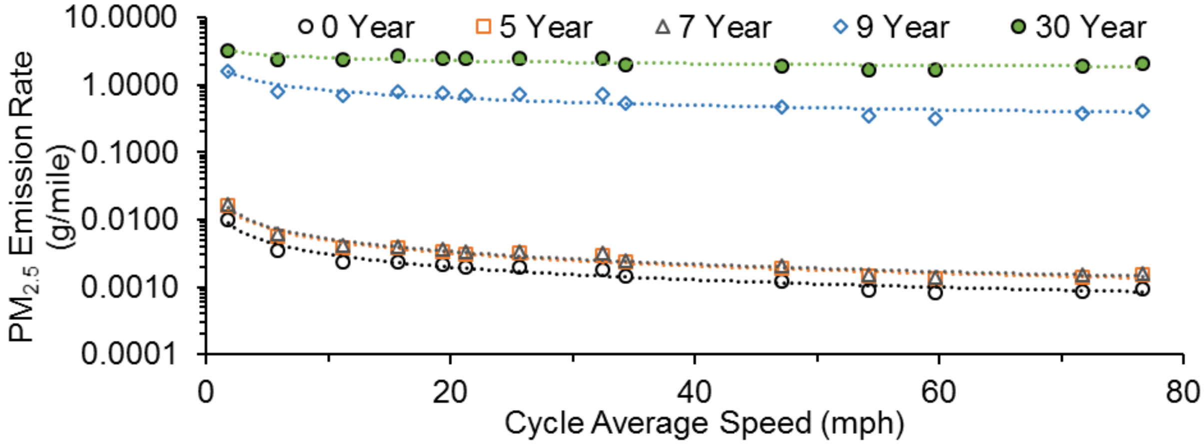


(b) Carbon Monoxide Emission Rates

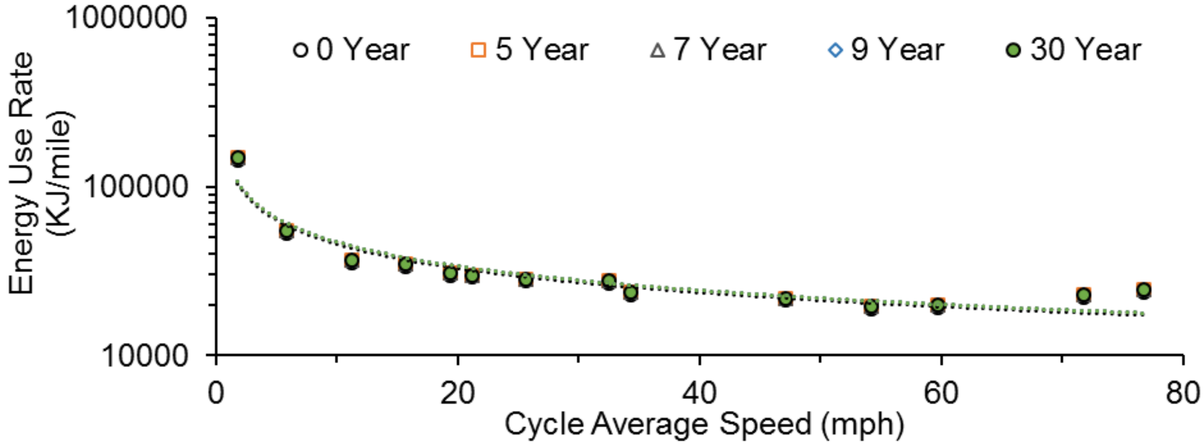


(c) Nitrogen Oxides Emission Rates

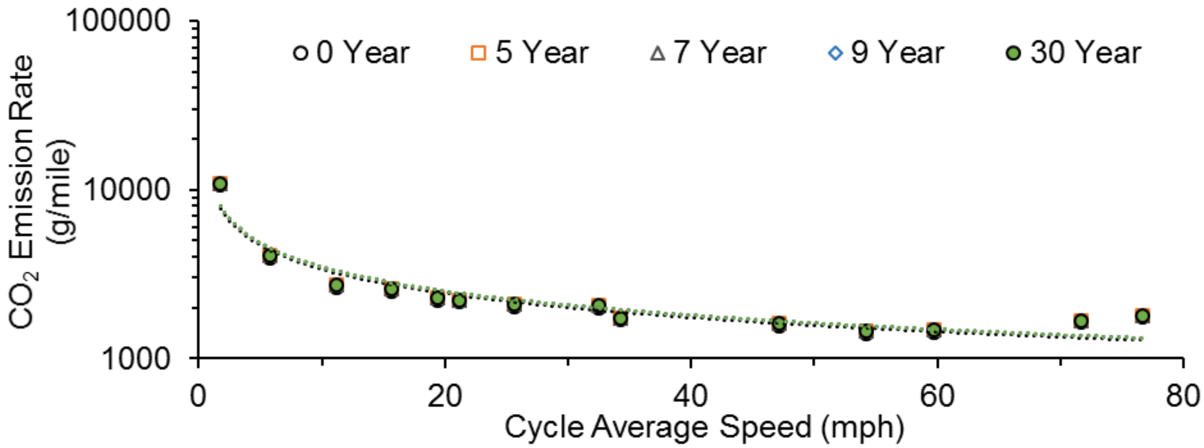
Figure 5. MOVES Cycle Average Emission and Energy Use Rates Versus Cycle Average Speed for Long-Haul Trucks (continued on next page).



(d) Fine Particulate Matter ($PM_{2.5}$) Emission Rates



(e) Energy Use Rates



(f) Carbon Dioxide Rates

Figure 5. MOVES Cycle Average Emission and Energy Use Rates Versus Cycle Average Speed for Long-Haul Trucks.

3.5 MODEL VERIFICATION

MOVES Lite was verified by comparing predicted cycle average emission rates from MOVES Lite to those from MOVES. Results for 0 year old SHT are given in Table 11. Results for 0 year old LHT are given in Table 12. Results for 5, 7, 9, 10, 15, and 30 year old SHT and LHT are given in the Appendix.

As shown in Table 11, the MOVES Lite predictions of cycle average HC emission rates for 0 year old SHT range from 0.04 g/mile to 1.16 g/mile. The MOVES predictions also range from 0.04 g/mile to 1.16 g/mile. The percent difference in MOVES Lite versus MOVES predicted emission rates for each cycle range from -0.2 percent to +0.4 percent. The average error is 0.08 percent. The relative errors are the same for a given cycle for all pollutants. For example, for CO2 emission rates, MOVES Lite predictions range from 61 g/mile to 10,440 g/mile, and MOVES predictions range from 661 g/mile to 10,416 g/mile. The average error is 0.08 percent for the CO_2 cycle average emission rates.

As shown in Table 12, the errors in predicted cycle average emission rates tend to be smaller for LHT than for SHT. For each pollutant, the errors range from -0.2 percent to +0.2 percent, with an average of 0.02 percent. The errors are the same for a given cycle when comparing pollutants. For example, cycle average NOx emission rates range from 0.81 g/mile to 8.42 g/mile based on MOVES Lite compared to a range of 0.81 g/mile to 8.40 g/mile based on MOVES.

The total number of verification cases includes:

- Two vehicle types
- 13 default driving cycles per vehicle type
- 5 pollutant emission rates and one energy use rate per cycle
- 7 ages (0, 5, 7, 9, 10, 15, and 30 years old)

Thus, there are 2×13×6×7 = 1,092 verification cases.

Based on the data given in the Appendix for the other ages for both SHT and LHT, it is clear that the relative errors are the same for a given vehicle type and driving cycle when comparing pollutants and ages. For example, the range of relative (percentage) errors in cycle average rates is the same for 30 year old SHT as for 0 year old SHT for NO_x emissions.

Cumulative distribution functions of the relative percentage errors are given in Figure 6 for SHT and Figure 7 for LHT. The trends in relative errors with respect to cycle average speed are given in Figure 8 for SHT and Figure 9 for LHT. The relative errors tend to be larger for lower cycle average speeds and to be close to zero for cycle average speeds greater than 50 mph.

With average errors of 0.08 percent for SHT and 0.02 percent for LHT, and errors for individual cycle average rates not exceeding ±0.5 percent, MOVES Lite is shown to accurately predict emission rates for SHT and LHT compared to MOVES.

Table 11. Example of Verification of MOVES Lite Compared to MOVES: 0 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	0.12	0.12	0.0	0.39	0.39	0.0	0.83	0.83	0.0	0.0007	0.0007	0.0	17175	17175	0.0	1272	1272	0.0
1	0.49	0.49	0.3	1.25	1.25	0.3	2.55	2.54	0.3	0.0023	0.0023	0.3	51044	50896	0.3	3781	3770	0.3
2	0.22	0.22	0.4	0.60	0.60	0.4	1.35	1.35	0.4	0.0012	0.0012	0.4	27526	27413	0.4	2039	2030	0.4
3	0.16	0.16	0.1	0.48	0.48	0.1	1.07	1.07	0.1	0.0009	0.0009	0.1	22017	21992	0.1	1631	1629	0.1
4	0.13	0.13	-0.2	0.41	0.41	-0.2	0.87	0.87	-0.2	0.0007	0.0007	-0.2	18660	18693	-0.2	1382	1385	-0.2
5	0.11	0.11	0.1	0.37	0.37	0.1	0.77	0.77	0.1	0.0006	0.0006	0.1	16689	16665	0.1	1236	1234	0.1
6	0.09	0.09	0.2	0.33	0.33	0.2	0.71	0.70	0.2	0.0006	0.0006	0.2	15565	15538	0.2	1153	1151	0.2
7	0.08	0.08	0.1	0.31	0.31	0.1	0.64	0.64	0.1	0.0005	0.0005	0.1	13652	13643	0.1	1011	1011	0.1
8	0.07	0.07	0.0	0.28	0.28	0.0	0.55	0.55	0.0	0.0005	0.0005	0.0	11564	11568	0.0	857	857	0.0
9	0.06	0.06	-0.1	0.25	0.25	-0.1	0.48	0.48	-0.1	0.0005	0.0005	-0.1	9789	9794	-0.1	725	725	-0.1
10	0.05	0.05	-0.1	0.23	0.23	-0.1	0.45	0.45	-0.1	0.0004	0.0004	-0.1	8920	8927	-0.1	661	661	-0.1
11	0.04	0.04	0.0	0.20	0.20	0.0	0.45	0.45	0.0	0.0004	0.0004	0.0	9708	9709	0.0	719	719	0.0
12	0.04	0.04	0.0	0.19	0.19	0.0	0.48	0.48	0.0	0.0004	0.0004	0.0	10741	10743	0.0	796	796	0.0
13	1.16	1.16	0.2	3.14	3.13	0.2	7.43	7.42	0.2	0.0065	0.0065	0.2	140955	140628	0.2	10440	10416	0.2

Table 12. Example of Verification of MOVES Lite Compared to MOVES: 0 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	0.12	0.12	0.0	0.43	0.43	0.0	1.35	1.35	0.0	0.0019	0.0019	0.0	29055	29055	0.0	2152	2152	0.0
1	0.43	0.43	0.0	1.11	1.11	0.0	2.92	2.92	0.0	0.0035	0.0035	0.0	53263	53259	0.0	3945	3945	0.0
2	0.23	0.23	0.0	0.64	0.64	0.0	1.86	1.86	0.0	0.0024	0.0024	0.0	35618	35619	0.0	2638	2638	0.0
3	0.16	0.16	0.0	0.52	0.52	0.0	1.64	1.64	0.0	0.0023	0.0023	0.0	33910	33904	0.0	2512	2511	0.0
4	0.13	0.13	-0.2	0.47	0.47	-0.2	1.42	1.42	-0.2	0.0021	0.0021	-0.2	29741	29795	-0.2	2203	2207	-0.2
5	0.11	0.11	-0.1	0.41	0.41	-0.1	1.24	1.24	-0.1	0.0020	0.0020	-0.1	27494	27519	-0.1	2036	2038	-0.1
6	0.08	0.08	0.1	0.35	0.35	0.1	1.17	1.17	0.1	0.0018	0.0018	0.1	26951	26923	0.1	1996	1994	0.1
7	0.08	0.08	0.1	0.34	0.34	0.1	1.03	1.02	0.1	0.0015	0.0015	0.1	22810	22782	0.1	1689	1687	0.1
8	0.06	0.06	0.0	0.29	0.29	0.0	0.90	0.90	0.0	0.0012	0.0012	0.0	21163	21163	0.0	1567	1567	0.0
9	0.06	0.06	0.0	0.27	0.27	0.0	0.81	0.81	0.0	0.0009	0.0009	0.0	18998	18992	0.0	1407	1407	0.0
10	0.05	0.05	0.0	0.26	0.26	0.0	0.82	0.82	0.0	0.0008	0.0008	0.0	19300	19294	0.0	1429	1429	0.0
11	0.04	0.04	0.0	0.22	0.22	0.0	0.91	0.91	0.0	0.0009	0.0009	0.0	22038	22032	0.0	1632	1632	0.0
12	0.04	0.04	0.0	0.20	0.20	0.0	0.96	0.96	0.0	0.0009	0.0009	0.0	23622	23616	0.0	1750	1749	0.0
13	1.15	1.14	0.2	3.09	3.08	0.2	8.42	8.40	0.2	0.0100	0.0100	0.2	143648	143315	0.2	10640	10615	0.2

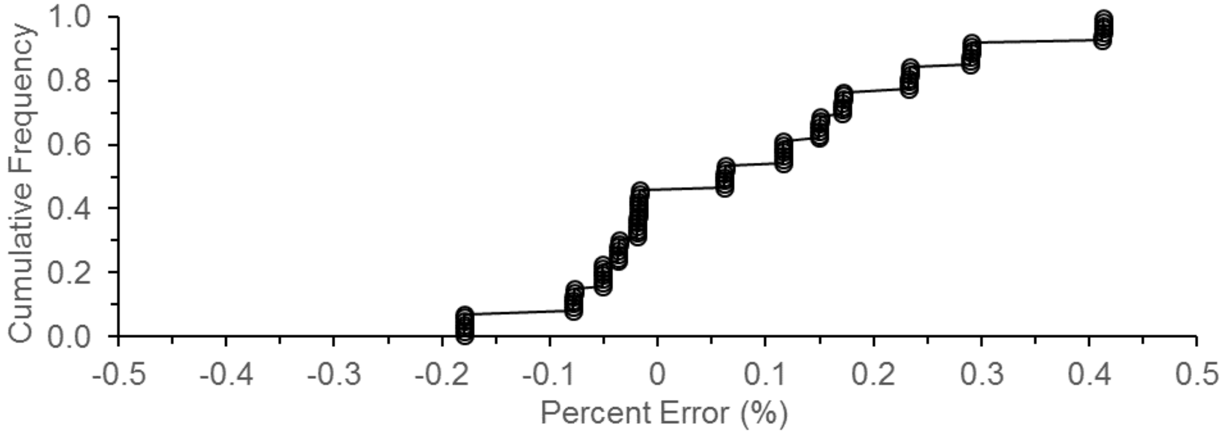


Figure 6. Distribution of Errors in MOVES Lite Cycle CO_2 Average Rate Estimates for Short-Haul Trucks, Ages 0, 5, 7, 9, 10, 15, and 30 years old (n=91). Results are similar for other pollutants.

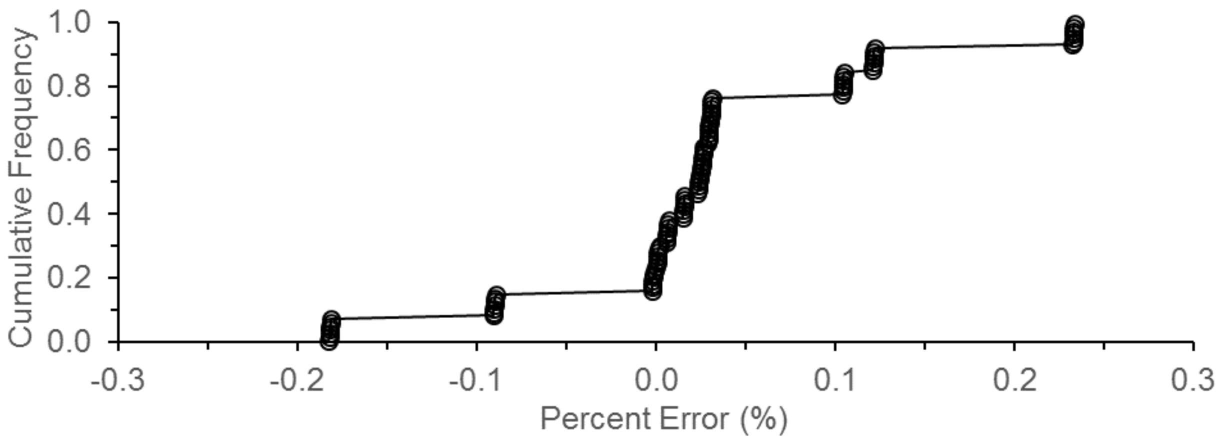


Figure 7. Distribution of Errors in MOVES Lite Cycle CO_2 Average Rate Estimates for Long-Haul Trucks, Ages 0, 5, 7, 9, 10, 15, and 30 years old (n=91). Results are similar for other pollutants.

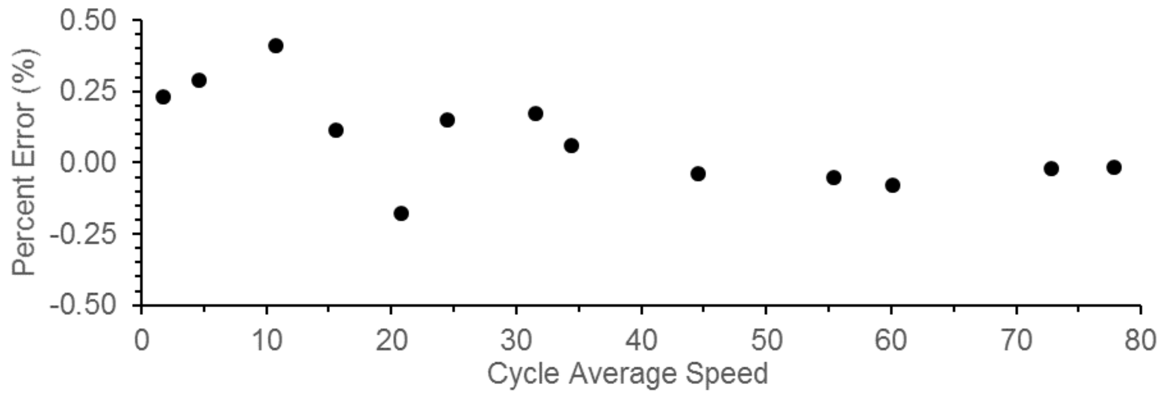


Figure 8. Errors in MOVES Lite Cycle CO_2 Average Rate Estimates for Short-Haul Trucks versus Cycle Average Speed, Ages 0 years old (n=13). Results are similar for other pollutants and ages.

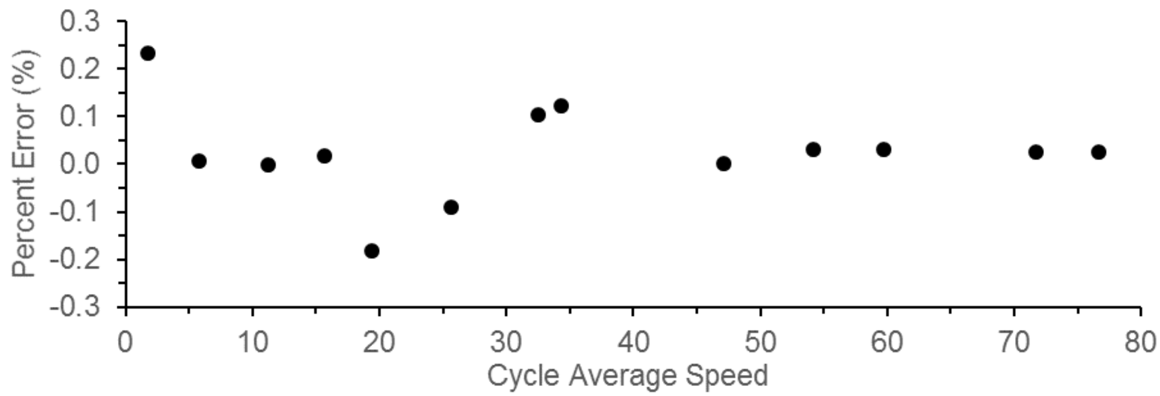


Figure 9. Errors in MOVES Lite Cycle CO_2 Average Rate Estimates for Long-Haul Trucks versus Cycle Average Speed, Ages 0 years old (n=13). Results are similar for other pollutants and ages.

4.0 CONCLUSIONS

A reduced form version of the U.S. Environmental Protection Agency's MOVES for heavy duty diesel vehicles used for freight transport was developed and verified. This reduced form model, referred to as MOVES Lite, is based on the same scaled tractive power (STP) operating modes (OpModes) that are used in MOVES. Here, MOVES Lite is developed for short-haul trucks (SHTs) and Long-Haul Trucks (LHT). SHTs include Class 6 and 7 trucks of 19,500 lbs to 33,000 lbs gross vehicle weight rating (GVWR), and LHTs include Class8a and Class 8B trucks of over 33,000 lbs GVWR.

For SHT and LHT, effective OpMode rates were estimated for vehicles that are 0, 5, 7, 9, 10, 15, 20, and 30 years old, to represent the timing of implementation of emission standards. The effective OpMode rates for emissions of HC, CO, NO_x, and $PM_{2.5}$ differ substantially with vehicle age. For example, for SHT, the emission rates for 0 year old vehicles are only 3.6%, 4.6%, 2.2%, and 0.10% of the rates for 30 year old vehicles for HC, CO, NO_x, and $PM_{2.5}$, respectively. These differences in emission rates are based on the implementation of emission control technologies such as exhaust gas recirculation (EGR), diesel oxidation catalyst (DOC), diesel particle filter (DPF), and selective catalytic reduction (SCR).

Base emission and energy use rates for the Federal Test Procedure (FTP) cycle are used in MOVES Lite as a basis for calibrating MOVES Lite to MOVES. For HC, NO_x, and CO, the MOVES estimates of base emission rates are shown to typically decrease with decreasing age in a step-wise manner for both SHT and LHT. These step decreases in emission rates are associated with the implementation of successively more stringent vehicle emission standards. $PM_{2.5}$ emission rates typically decrease from older to newer vehicles. Energy use rates are consistently higher for the larger, heavier LHT versus SHT.

MOVES includes 13 default driving cycles for SHTs and 13 default driving cycles for LHTs. The LHT default cycles are, in most cases, different than those for SHT. The range of average speeds for the default cycles are similar for the two vehicle types, ranging from 1.77 mph to 77.8 mph for SHT and from 1.77 mph to 76.7 mph for LHT. However, the range of cycle average STP is different, ranging from 0.0.4 skW/Mt to 5.21 skW/Mt for SHT and 0.10 skW/Mt to 11.64 skW/Mt for LHT. Although the speed profiles are not very different between the SHT and LHT default cycles, the cycle average STP tends to be higher for LHT. This is because the rolling resistance coefficient, rotating resistance coefficient, drag coefficient, and source mass factor are greater for LHT than for SHT. Thus, for a given speed and acceleration, STP tends to be greater for LHT than for SHT.

Typically, the cycle average HC and CO emission rates decrease with increasing cycle average speed for both SHT and LHT and for every vehicle age. Both cycle average speed and vehicle age are important determinants of cycle average emission rates. Cycle average NO_x emission rates are variable with cycle average speed and with vehicle age. The relative differences in these rates are greater with respect to age than with respect to cycle average speed. The cycle average NO_x emission rates reach a minimum around 60 mph, and increase slightly with higher speeds that are greater than 60 mph. Cycle average $PM_{2.5}$ emission rates are far more sensitive to vehicle age than to vehicle speed. These rates differ by more than three orders of magnitude when comparing 0 year old to 30 year old vehicles for a given cycle. The range of variability among driving cycles for a given age is less than an order-of-magnitude. The trends in energy use rates and CO_2 emission rates are similar. FThe rates reach a minimum at approximately 60 mph, and increase with higher speeds.

With average errors of 0.08 percent for SHT and 0.02 percent for LHT, and errors for individual cycle average rates not exceeding ±0.5 percent, MOVES Lite is shown to accurately predict emission rates for SHT and LHT compared to MOVES. Because many of the factors to which MOVES is sensitive are approximately constant during the time period of a typical TDM or TSM simulation, there is no need to run MOVES in its entirety for every link in a network. Thus, MOVES Lite is suitable for further use as a simplified alternative to MOVES, especially for integration with traffic simulation models such as DTAlite.

5.0 REFERENCES

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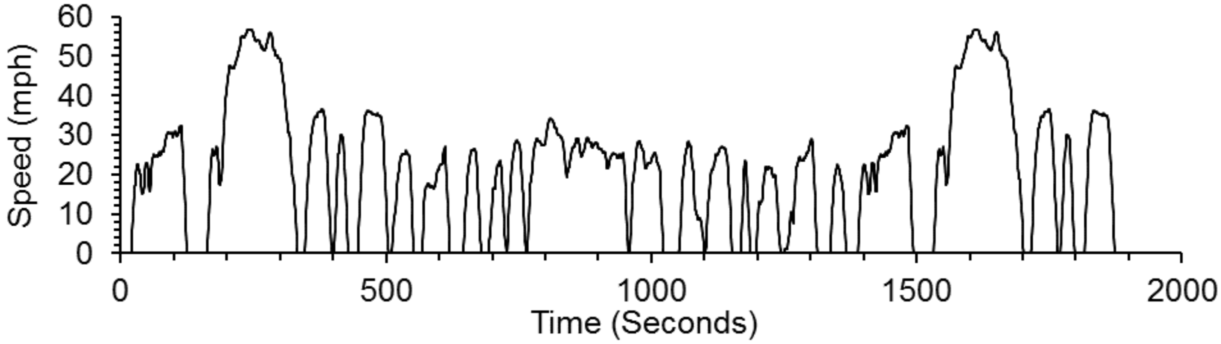
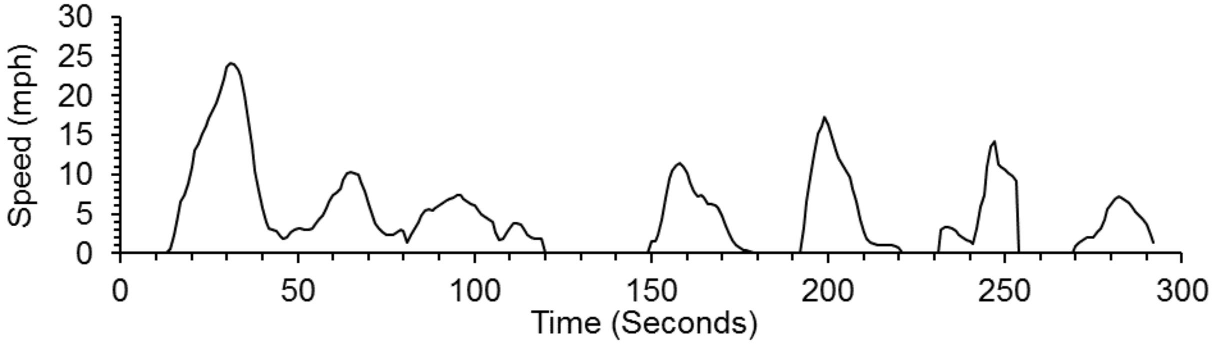
APPENDIX

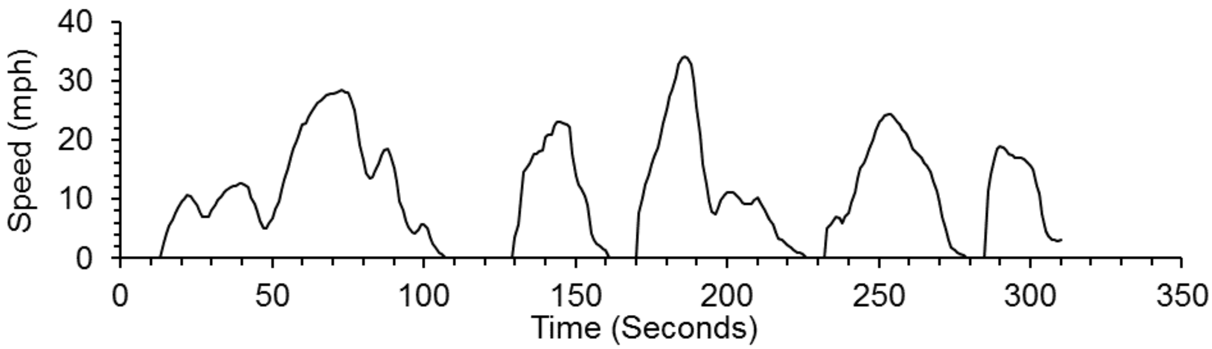
MOVES DEFAULT DRIVING CYCLES AND MOVES LITE VERIFICATION RESULTS



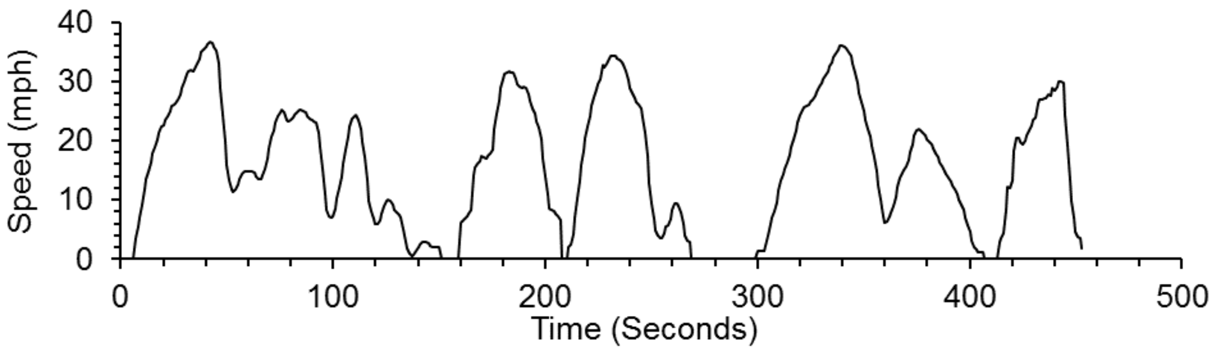
(a) Base Cycle



(b) Cycle 201

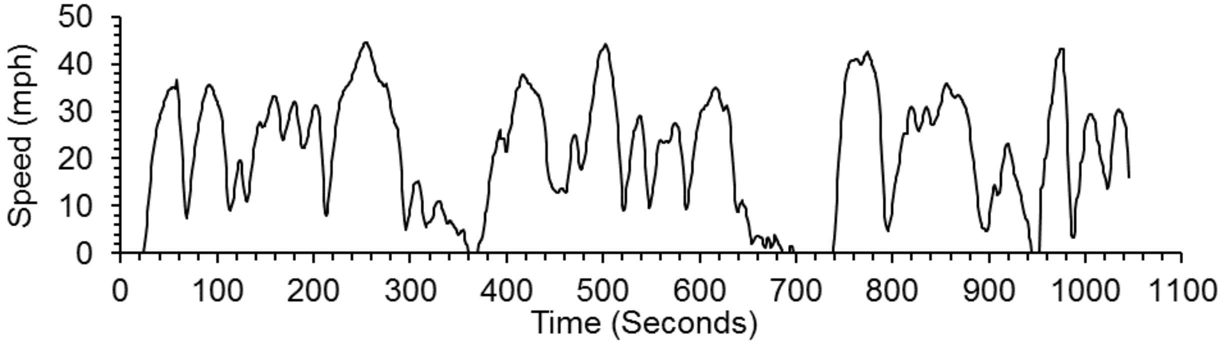


(c) Cycle 202

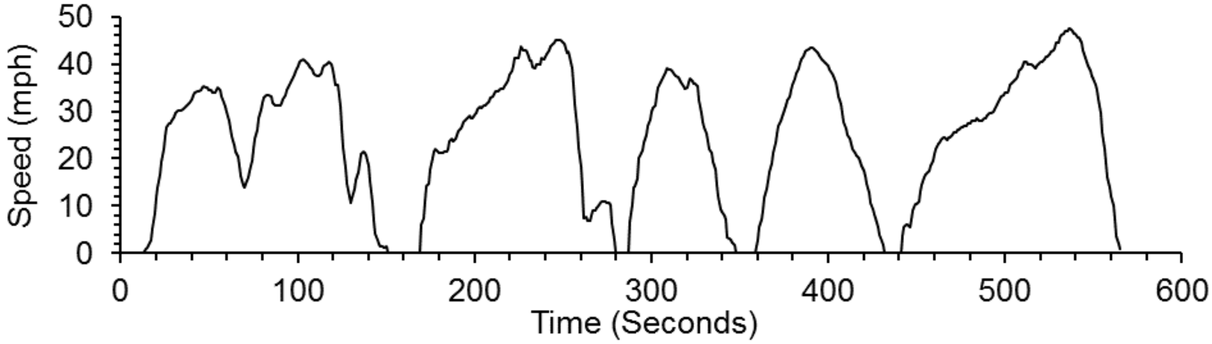


(d) Cycle 203

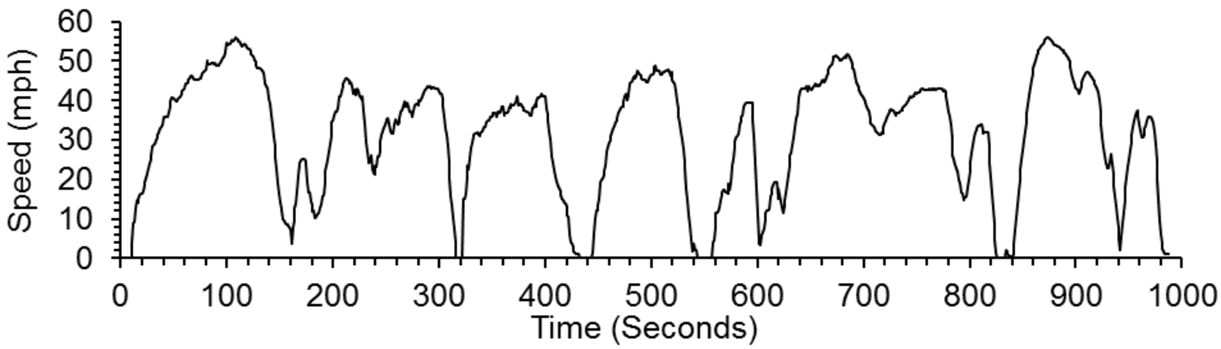
Figure A-1. Base Cycle (a) and MOVES Default Cycles (b-n) for Short Haul Trucks (continued on next page)



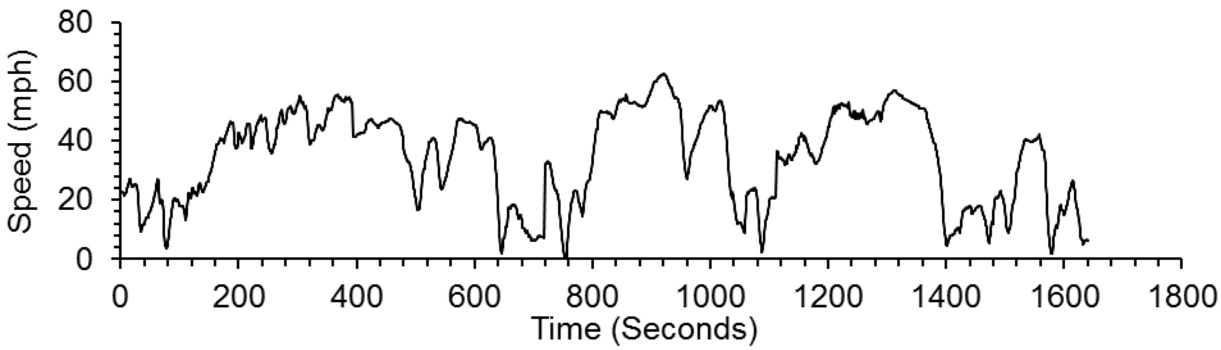
(e) Cycle 204



(f) Cycle 205

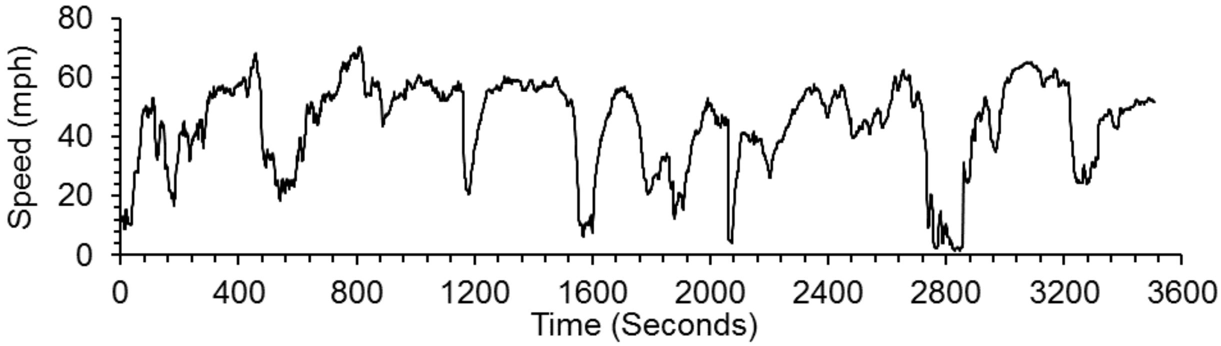


(g) Cycle 206

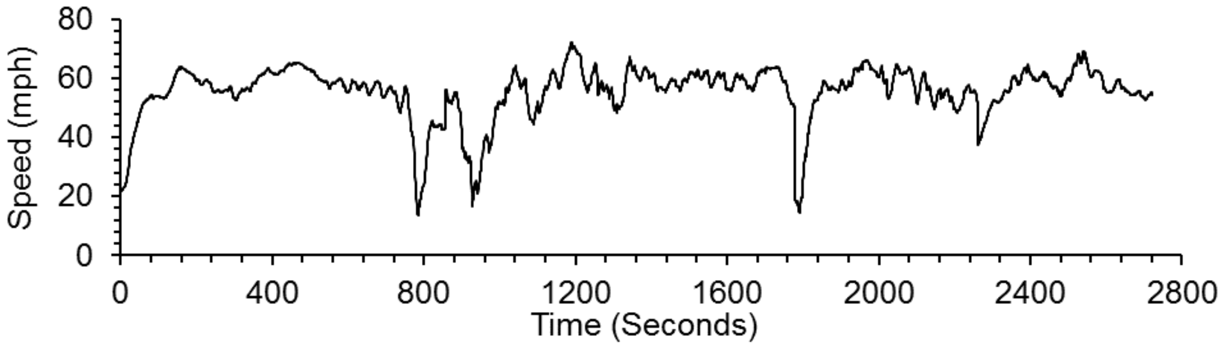


(h) Cycle 251

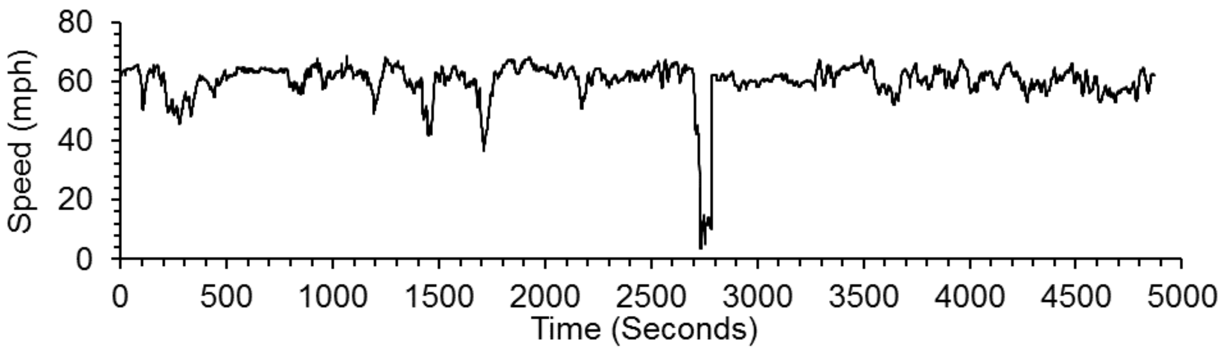
Figure A-1. Base Cycle (a) and MOVES Default Cycles (b-n) for Short Haul Trucks (continued on next page)



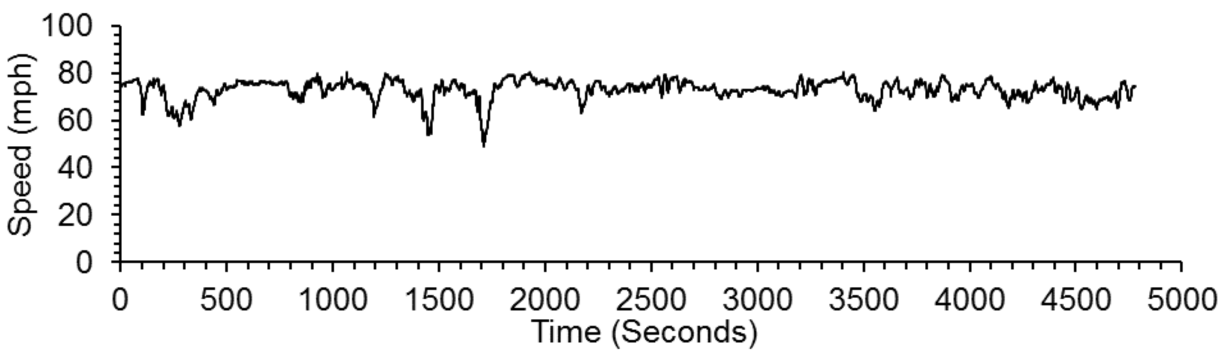
(i) Cycle 252



(j) Cycle 253

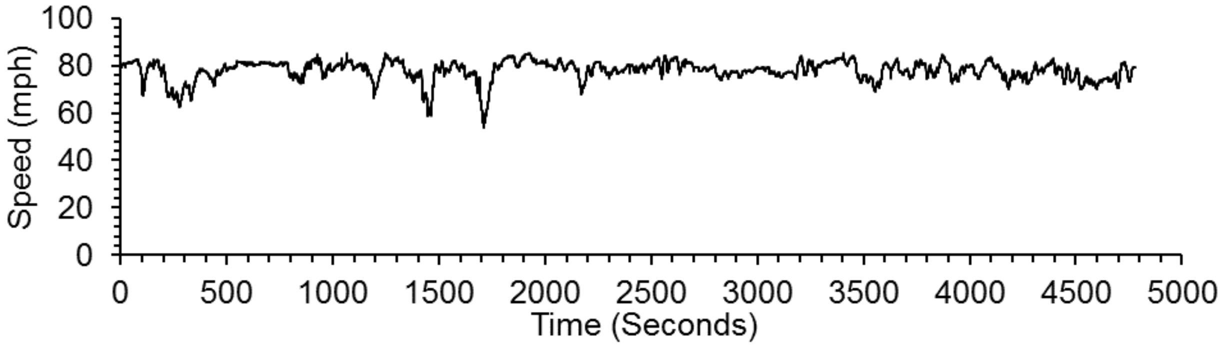


(k) Cycle 254

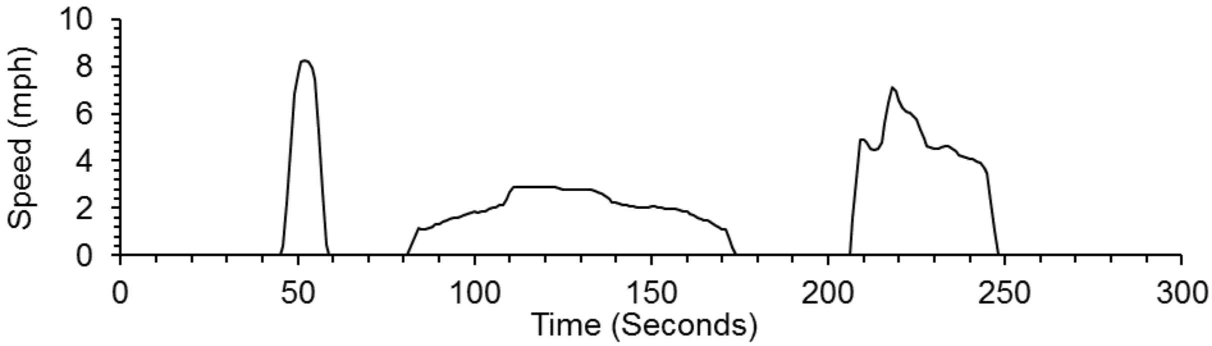


(l) Cycle 255

Figure A-1. Base Cycle (a) and MOVES Default Cycles (b-n) for Short Haul Trucks (continued on next page)

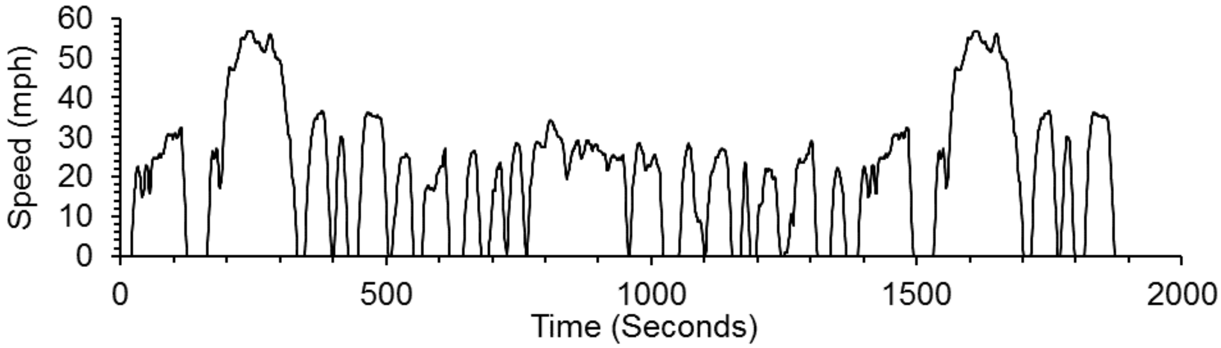


(m) Cycle 397

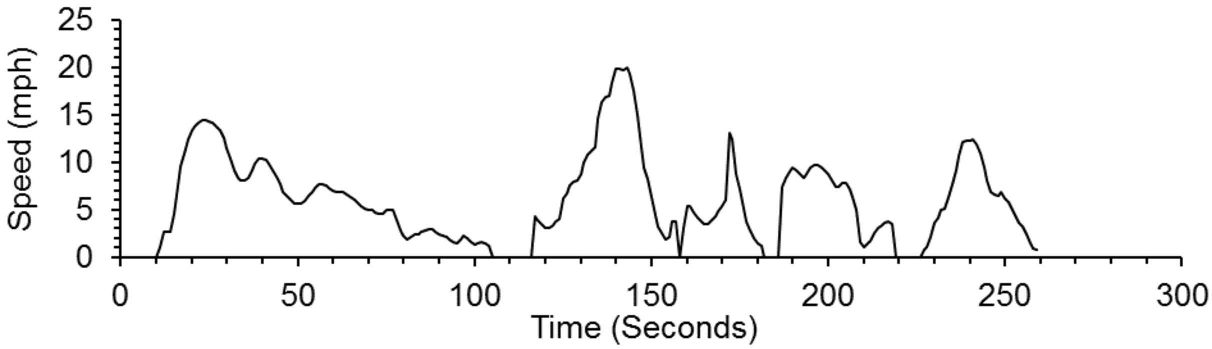


(n) Cycle 398

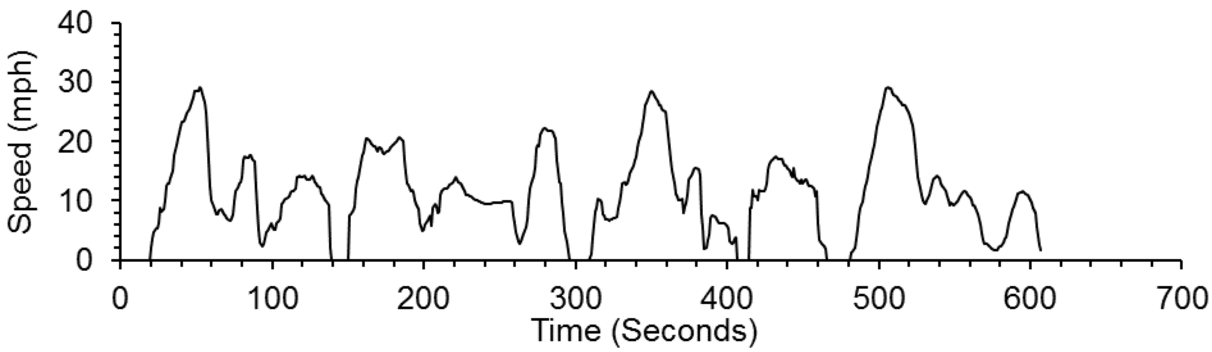
Figure A-1. Base Cycle (a) and MOVES Default Cycles (b-n) for Short Haul Trucks.



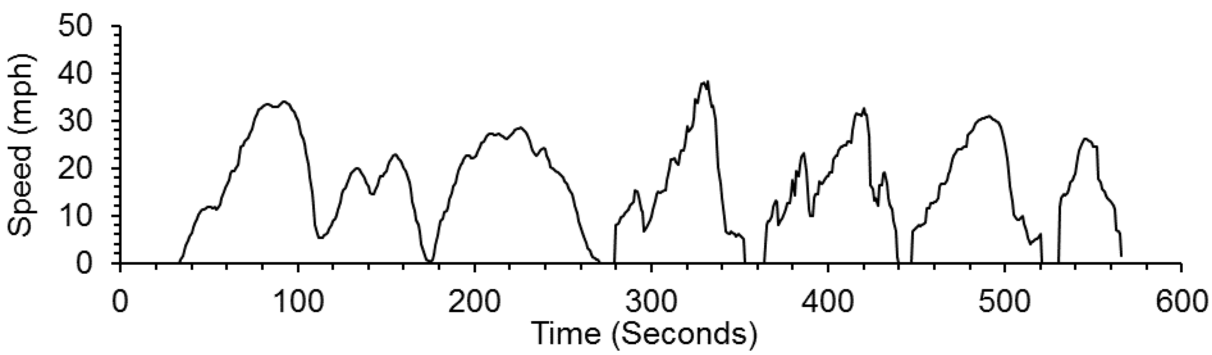
(a) Base Cycle



(b) Cycle 301

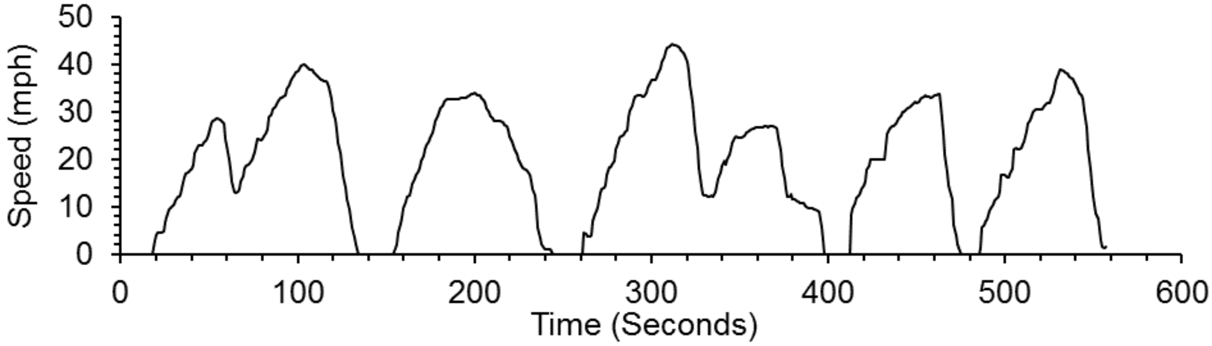


(c) Cycle 302

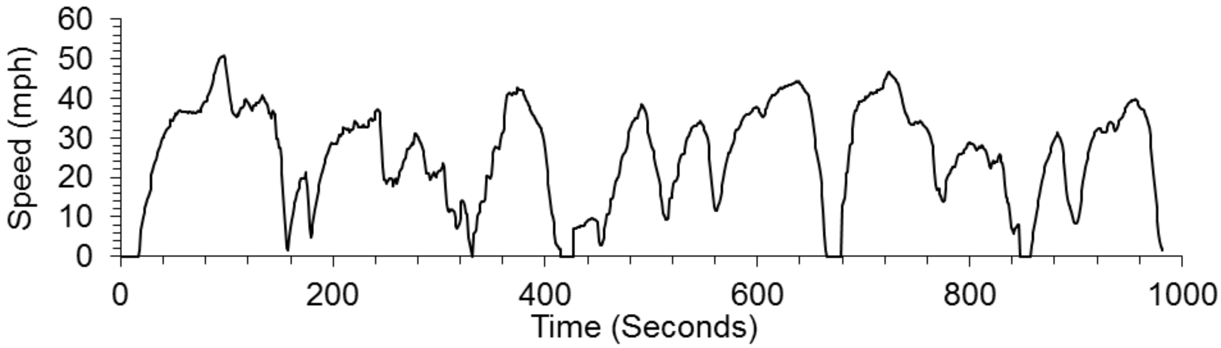


(d) Cycle 303

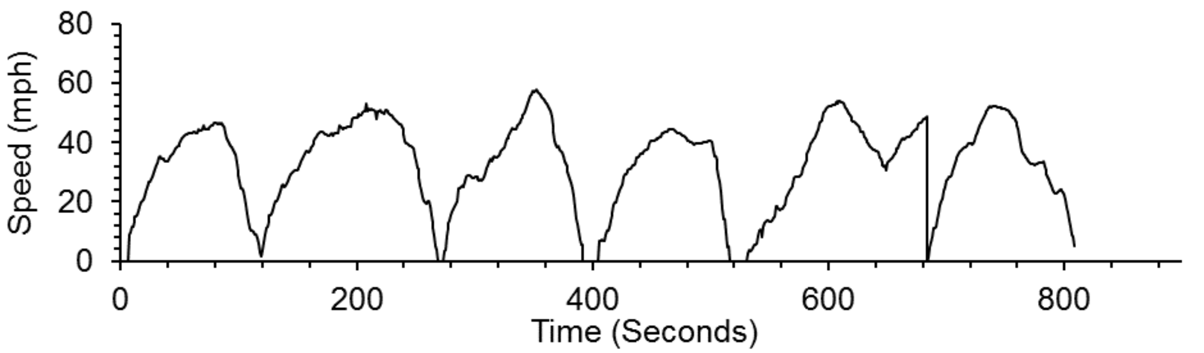
Figure A-2. Base Cycle (a) and MOVES Default Cycles (b-n) for Long Haul Trucks (continued on next page).



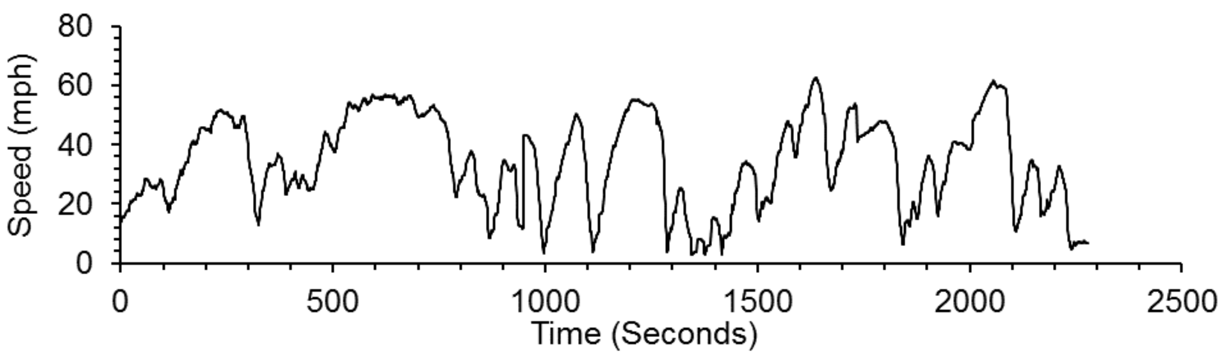
(e) Cycle 304



(f) Cycle 305

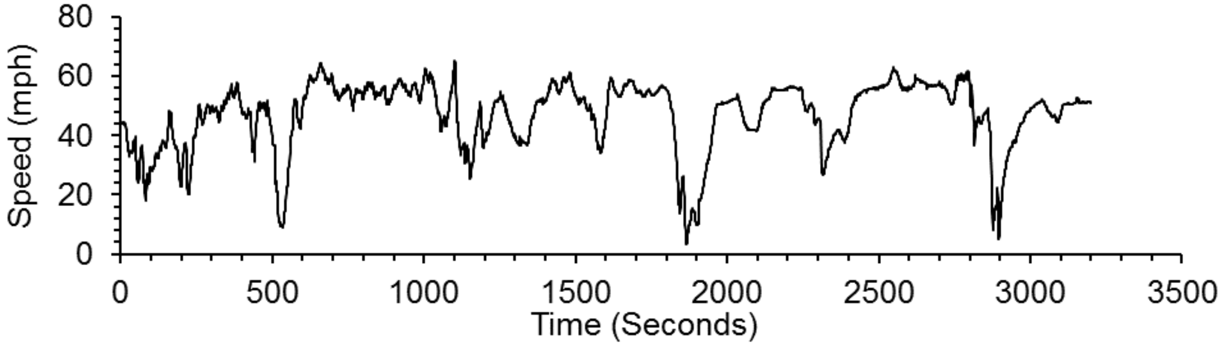


(g) Cycle 306

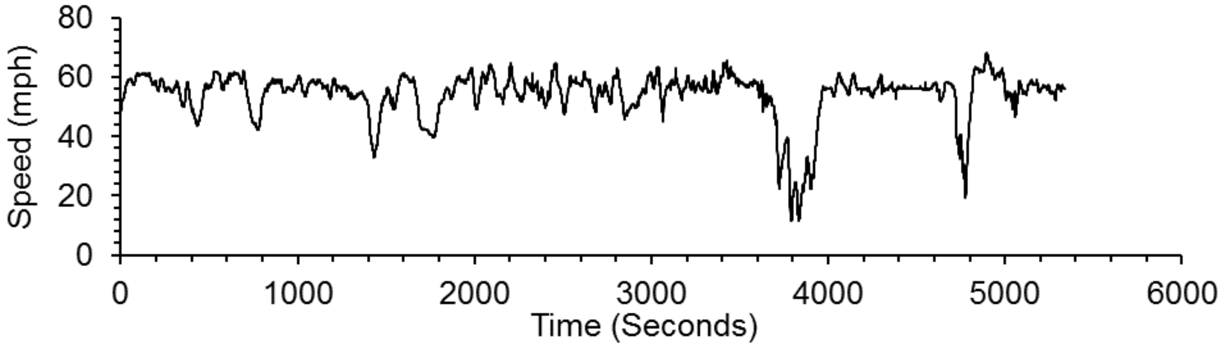


(h) Cycle 351

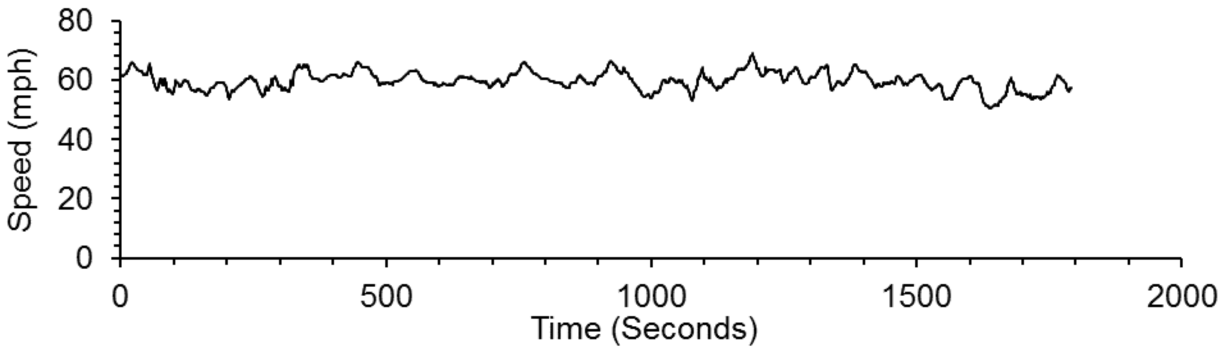
Figure A-2. Base Cycle (a) and MOVES Default Cycles (b-n) for Long Haul Trucks (continued on next page).



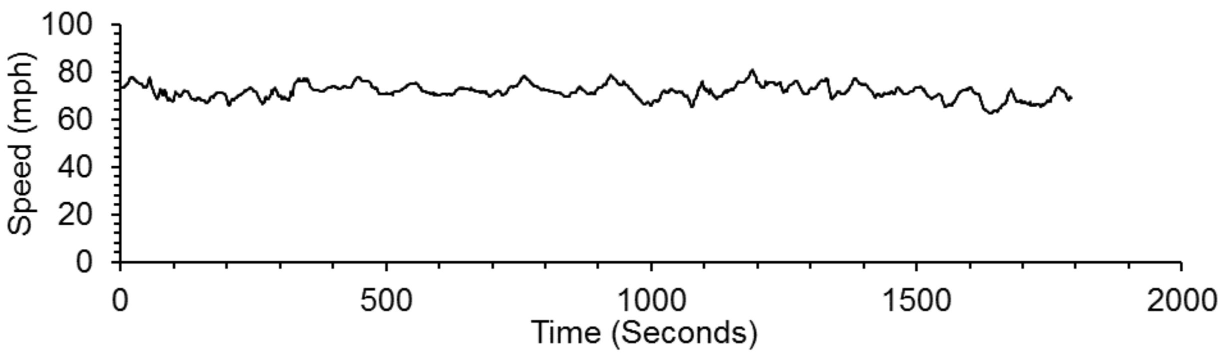
(i) Cycle 352



(j) Cycle 353

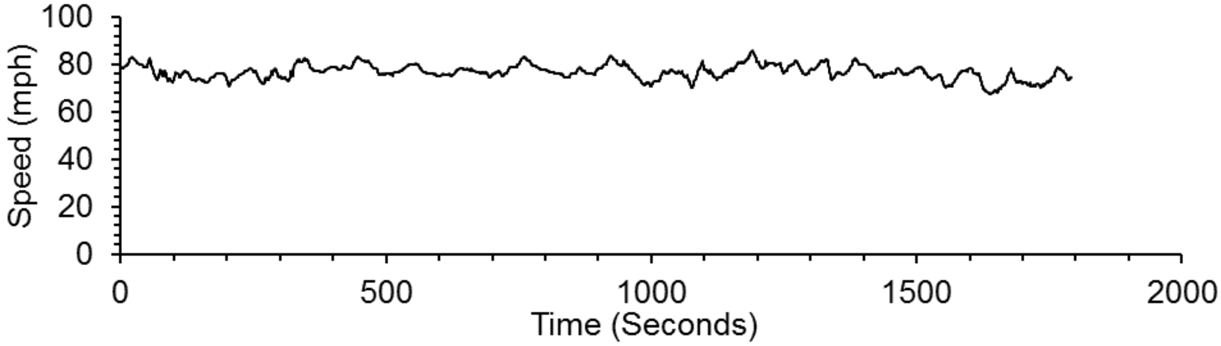


(k) Cycle 354

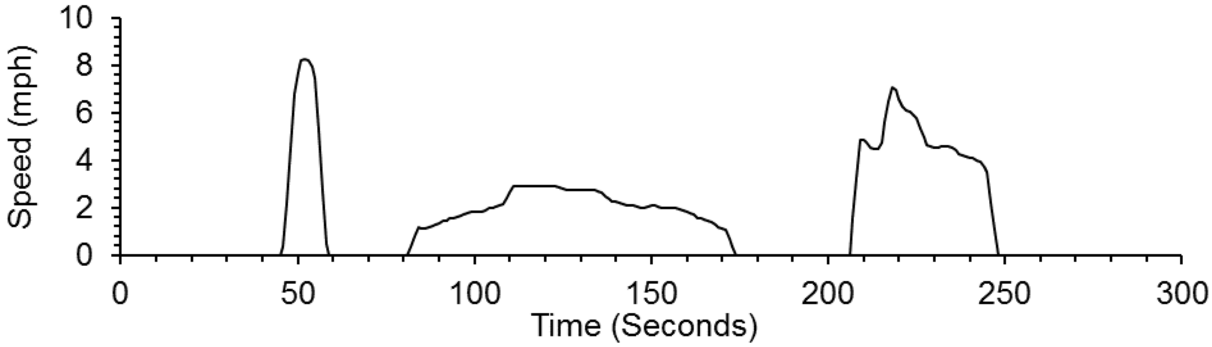


(l) Cycle 355

Figure A-2. Base Cycle (a) and MOVES Default Cycles (b-n) for Long Haul Trucks (continued on next page).



(m) Cycle 396



(n) Cycle 398

Figure A-2. Base Cycle (a) and MOVES Default Cycles (b-n) for Long Haul Trucks

Table A-1. Verification of MOVES Lite Compared to MOVES: 5 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	0.14	0.14	0.0	0.48	0.48	0.0	1.31	1.31	0.0	0.0012	0.0012	0.0	18079	18079	0.0	1339	1339	0.0
1	0.59	0.59	0.3	1.53	1.53	0.3	4.00	3.99	0.3	0.0039	0.0039	0.3	53731	53575	0.3	3980	3968	0.3
2	0.27	0.27	0.4	0.73	0.73	0.4	2.12	2.11	0.4	0.0019	0.0019	0.4	28975	28856	0.4	2146	2137	0.4
3	0.20	0.20	0.1	0.58	0.58	0.1	1.67	1.67	0.1	0.0014	0.0014	0.1	23176	23149	0.1	1717	1715	0.1
4	0.15	0.15	-0.2	0.50	0.50	-0.2	1.36	1.36	-0.2	0.0012	0.0012	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	0.13	0.13	0.1	0.45	0.45	0.1	1.21	1.20	0.1	0.0010	0.0010	0.1	17568	17542	0.1	1301	1299	0.1
6	0.11	0.11	0.2	0.40	0.40	0.2	1.11	1.11	0.2	0.0010	0.0010	0.2	16384	16356	0.2	1214	1211	0.2
7	0.10	0.10	0.1	0.38	0.38	0.1	1.00	1.00	0.1	0.0009	0.0009	0.1	14370	14361	0.1	1064	1064	0.1
8	0.08	0.08	0.0	0.34	0.34	0.0	0.86	0.86	0.0	0.0008	0.0008	0.0	12173	12177	0.0	902	902	0.0
9	0.07	0.07	-0.1	0.31	0.31	-0.1	0.76	0.76	-0.1	0.0008	0.0008	-0.1	10304	10310	-0.1	763	764	-0.1
10	0.07	0.07	-0.1	0.29	0.29	-0.1	0.70	0.70	-0.1	0.0007	0.0007	-0.1	9389	9396	-0.1	695	696	-0.1
11	0.05	0.05	0.0	0.25	0.25	0.0	0.71	0.71	0.0	0.0006	0.0006	0.0	10219	10221	0.0	757	757	0.0
12	0.05	0.05	0.0	0.24	0.24	0.0	0.75	0.75	0.0	0.0006	0.0006	0.0	11307	11309	0.0	837	838	0.0
13	1.42	1.42	0.2	3.83	3.82	0.2	11.67	11.64	0.2	0.0108	0.0107	0.2	148374	148030	0.2	10990	10964	0.2

Table A-2. Verification of MOVES Lite Compared to MOVES: 7 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	0.26	0.26	0.0	0.88	0.88	0.0	3.97	3.97	0.0	0.0013	0.0013	0.0	18079	18079	0.0	1339	1339	0.0
1	1.09	1.09	0.3	2.81	2.80	0.3	12.15	12.12	0.3	0.0044	0.0044	0.3	53731	53575	0.3	3980	3968	0.3
2	0.49	0.49	0.4	1.34	1.34	0.4	6.45	6.42	0.4	0.0022	0.0022	0.4	28975	28856	0.4	2146	2137	0.4
3	0.36	0.36	0.1	1.07	1.07	0.1	5.08	5.08	0.1	0.0016	0.0016	0.1	23176	23149	0.1	1717	1715	0.1
4	0.28	0.28	-0.2	0.91	0.91	-0.2	4.14	4.15	-0.2	0.0013	0.0013	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	0.24	0.24	0.2	0.83	0.83	0.1	3.66	3.66	0.1	0.0012	0.0012	0.1	17568	17542	0.1	1301	1299	0.1
6	0.20	0.20	0.2	0.73	0.73	0.2	3.36	3.36	0.2	0.0011	0.0011	0.2	16384	16356	0.2	1214	1211	0.2
7	0.19	0.19	0.1	0.69	0.69	0.1	3.03	3.03	0.1	0.0010	0.0010	0.1	14370	14361	0.1	1064	1064	0.1
8	0.16	0.16	0.0	0.63	0.63	0.0	2.61	2.61	0.0	0.0009	0.0009	0.0	12173	12177	0.0	902	902	0.0
9	0.13	0.13	-0.1	0.56	0.56	-0.1	2.31	2.31	-0.1	0.0009	0.0009	-0.1	10304	10310	-0.1	763	764	-0.1
10	0.12	0.12	-0.1	0.53	0.53	-0.1	2.13	2.13	-0.1	0.0008	0.0008	-0.1	9389	9397	-0.1	695	696	-0.1
11	0.10	0.10	0.0	0.45	0.45	0.0	2.15	2.15	0.0	0.0007	0.0007	0.0	10219	10220	0.0	757	757	0.0
12	0.09	0.09	0.0	0.43	0.44	0.0	2.28	2.28	0.0	0.0007	0.0007	0.0	11307	11309	0.0	837	838	0.0
13	2.61	2.60	0.2	7.03	7.02	0.2	35.44	35.36	0.2	0.0123	0.0123	0.2	148375	148029	0.2	10990	10964	0.2

Table A-3. Verification of MOVES Lite Compared to MOVES: 9 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	1.27	1.27	0.0	4.22	4.22	0.0	7.99	7.99	0.0	0.1845	0.1845	0.0	18079	18079	0.0	1339	1339	0.0
1	5.26	5.25	0.3	13.54	13.50	0.3	24.44	24.37	0.3	0.5215	0.5200	0.3	53730	53575	0.3	3980	3968	0.3
2	2.37	2.36	0.4	6.49	6.46	0.4	12.96	12.91	0.4	0.2955	0.2942	0.4	28975	28856	0.4	2146	2137	0.4
3	1.74	1.74	0.1	5.15	5.15	0.1	10.23	10.21	0.1	0.2129	0.2127	0.1	23176	23149	0.1	1717	1715	0.1
4	1.36	1.37	-0.2	4.40	4.41	-0.2	8.32	8.34	-0.2	0.1822	0.1825	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	1.16	1.16	0.1	4.02	4.02	0.1	7.36	7.35	0.1	0.1557	0.1555	0.1	17568	17542	0.1	1301	1299	0.1
6	0.94	0.94	0.2	3.53	3.52	0.2	6.76	6.75	0.2	0.1748	0.1745	0.2	16384	16356	0.2	1214	1211	0.2
7	0.92	0.92	0.1	3.35	3.35	0.1	6.10	6.10	0.1	0.1481	0.1480	0.1	14370	14361	0.1	1064	1064	0.1
8	0.75	0.75	0.0	3.03	3.03	0.0	5.26	5.26	0.0	0.1465	0.1465	0.0	12173	12177	0.0	902	902	0.0
9	0.63	0.63	-0.1	2.72	2.73	-0.1	4.65	4.65	-0.1	0.1546	0.1546	-0.1	10304	10310	-0.1	763	764	-0.1
10	0.58	0.58	-0.1	2.54	2.54	-0.1	4.29	4.29	-0.1	0.1467	0.1468	-0.1	9389	9397	-0.1	695	696	-0.1
11	0.48	0.48	0.0	2.19	2.19	0.0	4.33	4.33	0.0	0.1486	0.1486	0.0	10218	10220	0.0	757	757	0.0
12	0.44	0.44	0.0	2.10	2.10	0.0	4.59	4.59	0.0	0.1574	0.1574	0.0	11306	11309	0.0	837	838	0.0
13	12.58	12.55	0.2	33.94	33.87	0.2	71.27	71.11	0.2	1.3993	1.3960	0.2	148374	148029	0.2	10990	10964	0.2

Table A-4. Verification of MOVES Lite Compared to MOVES: 10 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	1.27	1.27	0.0	4.22	4.22	0.0	7.99	7.99	0.0	0.1845	0.1845	0.0	18079	18079	0.0	1339	1339	0.0
1	5.26	5.25	0.3	13.54	13.50	0.3	24.44	24.37	0.3	0.5215	0.5200	0.3	53730	53575	0.3	3980	3968	0.3
2	2.37	2.36	0.4	6.49	6.46	0.4	12.96	12.91	0.4	0.2955	0.2942	0.4	28975	28856	0.4	2146	2137	0.4
3	1.74	1.74	0.1	5.15	5.15	0.1	10.23	10.21	0.1	0.2129	0.2127	0.1	23176	23149	0.1	1717	1715	0.1
4	1.36	1.37	-0.2	4.40	4.41	-0.2	8.32	8.34	-0.2	0.1822	0.1825	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	1.16	1.16	0.1	4.02	4.02	0.1	7.36	7.35	0.1	0.1557	0.1555	0.2	17568	17542	0.1	1301	1299	0.1
6	0.94	0.94	0.2	3.53	3.52	0.2	6.76	6.75	0.2	0.1748	0.1745	0.2	16384	16356	0.2	1214	1211	0.2
7	0.92	0.92	0.1	3.35	3.35	0.1	6.10	6.10	0.1	0.1481	0.1480	0.1	14370	14361	0.1	1064	1064	0.1
8	0.75	0.75	0.0	3.03	3.03	0.0	5.26	5.26	0.0	0.1465	0.1465	0.0	12173	12177	0.0	902	902	0.0
9	0.63	0.63	-0.1	2.72	2.73	-0.1	4.65	4.65	-0.1	0.1546	0.1546	-0.1	10304	10310	-0.1	763	764	-0.1
10	0.58	0.58	-0.1	2.54	2.54	-0.1	4.29	4.29	-0.1	0.1467	0.1468	-0.1	9389	9396	-0.1	695	696	-0.1
11	0.48	0.48	0.0	2.19	2.19	0.0	4.33	4.33	0.0	0.1486	0.1486	0.0	10219	10220	0.0	757	757	0.0
12	0.44	0.44	0.0	2.10	2.10	0.0	4.59	4.59	0.0	0.1574	0.1574	0.0	11307	11309	0.0	837	838	0.0
13	12.58	12.55	0.2	33.95	33.87	0.2	71.28	71.11	0.2	1.3993	1.3960	0.2	148374	148029	0.2	10990	10964	0.2

Table A-5. Verification of MOVES Lite Compared to MOVES: 15 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	2.36	2.36	0.0	5.99	5.99	0.0	8.62	8.62	0.0	0.2046	0.2046	0.0	18079	18079	0.0	1339	1339	0.0
1	8.64	8.61	0.3	18.04	17.99	0.3	28.15	28.07	0.3	0.5784	0.5767	0.3	53731	53575	0.3	3980	3968	0.3
2	4.11	4.09	0.4	9.52	9.48	0.4	14.59	14.53	0.4	0.3277	0.3264	0.4	28975	28856	0.4	2146	2137	0.4
3	3.10	3.09	0.1	7.60	7.59	0.1	11.07	11.06	0.1	0.2361	0.2359	0.1	23176	23149	0.1	1717	1715	0.1
4	2.50	2.51	-0.2	6.53	6.54	-0.2	9.19	9.20	-0.2	0.2021	0.2024	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	2.17	2.16	0.1	5.73	5.72	0.2	8.09	8.08	0.1	0.1727	0.1724	0.1	17568	17542	0.1	1301	1299	0.1
6	1.80	1.80	0.2	5.01	5.00	0.2	7.71	7.69	0.2	0.1939	0.1936	0.2	16384	16356	0.2	1214	1211	0.2
7	1.67	1.66	0.1	4.51	4.50	0.1	6.68	6.68	0.1	0.1643	0.1642	0.1	14370	14361	0.1	1064	1064	0.1
8	1.38	1.38	0.0	3.79	3.80	0.0	5.71	5.72	0.0	0.1624	0.1625	0.0	12173	12177	0.0	902	902	0.0
9	1.15	1.15	-0.1	3.15	3.16	-0.1	5.01	5.01	-0.1	0.1714	0.1715	-0.1	10304	10309	-0.1	763	764	-0.1
10	1.07	1.07	-0.1	2.90	2.90	-0.1	4.61	4.61	-0.1	0.1627	0.1628	-0.1	9389	9396	-0.1	695	696	-0.1
11	0.89	0.89	0.0	2.49	2.49	0.0	5.14	5.14	0.0	0.1648	0.1649	0.0	10219	10220	0.0	757	757	0.0
12	0.84	0.84	0.0	2.40	2.40	0.0	5.74	5.74	0.0	0.1745	0.1746	0.0	11307	11308	0.0	837	838	0.0
13	20.09	20.04	0.2	40.37	40.28	0.2	82.10	81.91	0.2	1.5520	1.5484	0.2	148374	148029	0.2	10990	10964	0.2

Table A-6. Verification of MOVES Lite Compared to MOVES: 30 Year Old Short Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES-Lite (g/mi)	MOVES (g/mi)	% diff
0	2.36	2.36	0.0	5.99	5.99	0.0	25.43	25.43	0.0	0.4724	0.4724	0.0	18079	18079	0.0	1339	1339	0.0
1	8.64	8.61	0.3	18.04	17.99	0.3	79.91	79.67	0.3	1.0815	1.0784	0.3	53731	53575	0.3	3980	3968	0.3
2	4.11	4.09	0.4	9.52	9.48	0.4	41.54	41.37	0.4	0.6818	0.6790	0.4	28975	28856	0.4	2146	2137	0.4
3	3.10	3.09	0.1	7.60	7.59	0.1	33.46	33.42	0.1	0.5355	0.5349	0.1	23176	23150	0.1	1717	1715	0.1
4	2.50	2.51	-0.2	6.53	6.54	-0.2	28.67	28.72	-0.2	0.4829	0.4838	-0.2	19642	19677	-0.2	1455	1457	-0.2
5	2.17	2.16	0.2	5.73	5.72	0.1	25.93	25.90	0.1	0.4139	0.4133	0.1	17568	17542	0.1	1301	1299	0.1
6	1.80	1.80	0.2	5.01	5.00	0.2	23.57	23.53	0.2	0.4602	0.4594	0.2	16384	16356	0.2	1214	1211	0.2
7	1.67	1.66	0.1	4.51	4.50	0.1	20.16	20.14	0.1	0.4177	0.4175	0.1	14370	14361	0.1	1064	1064	0.1
8	1.38	1.38	0.0	3.79	3.80	0.0	15.96	15.97	0.0	0.4263	0.4264	0.0	12173	12177	0.0	902	902	0.0
9	1.15	1.15	-0.1	3.15	3.16	-0.1	11.93	11.94	-0.1	0.4426	0.4428	-0.1	10304	10309	-0.1	763	764	-0.1
10	1.07	1.07	-0.1	2.90	2.90	-0.1	10.39	10.40	-0.1	0.4256	0.4260	-0.1	9389	9396	-0.1	695	696	-0.1
11	0.89	0.89	0.0	2.49	2.49	0.0	13.46	13.47	0.0	0.4061	0.4061	0.0	10219	10220	0.0	757	757	0.0
12	0.84	0.84	0.0	2.40	2.40	0.0	16.20	16.20	0.0	0.4133	0.4134	0.0	11307	11309	0.0	837	838	0.0
13	20.09	20.04	0.2	40.37	40.28	0.2	231.90	231.36	0.2	2.2925	2.2872	0.2	148375	148030	0.2	10990	10964	0.2

Table A-7. Verification of MOVES Lite Compared to MOVES: 5 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	0.14	0.14	0.0	0.53	0.53	0.0	2.08	2.08	0.0	0.0031	0.0031	0.0	29954	29954	0.0	2219	2219	0.0
1	0.53	0.53	0.0	1.36	1.36	0.0	4.52	4.52	0.0	0.0057	0.0057	0.0	54910	54907	0.0	4067	4067	0.0
2	0.28	0.28	0.0	0.79	0.79	0.0	2.89	2.89	0.0	0.0039	0.0039	0.0	36720	36720	0.0	2720	2720	0.0
3	0.20	0.20	0.0	0.64	0.64	0.0	2.54	2.54	0.0	0.0038	0.0038	0.0	34958	34953	0.0	2589	2589	0.0
4	0.16	0.16	-0.2	0.57	0.57	-0.2	2.20	2.21	-0.2	0.0034	0.0034	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.13	0.13	-0.1	0.50	0.50	-0.1	1.93	1.93	-0.1	0.0032	0.0032	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.10	0.10	0.1	0.43	0.43	0.1	1.81	1.81	0.1	0.0030	0.0030	0.1	27785	27756	0.1	2058	2056	0.1
7	0.10	0.10	0.1	0.42	0.42	0.1	1.59	1.59	0.1	0.0023	0.0023	0.1	23515	23487	0.1	1742	1740	0.1
8	0.08	0.08	0.0	0.35	0.35	0.0	1.39	1.39	0.0	0.0019	0.0019	0.0	21817	21817	0.0	1616	1616	0.0
9	0.07	0.07	0.0	0.33	0.33	0.0	1.26	1.26	0.0	0.0014	0.0014	0.0	19585	19579	0.0	1451	1450	0.0
10	0.06	0.06	0.0	0.31	0.31	0.0	1.28	1.27	0.0	0.0013	0.0013	0.0	19897	19891	0.0	1474	1473	0.0
11	0.05	0.05	0.0	0.26	0.26	0.0	1.41	1.41	0.0	0.0014	0.0014	0.0	22720	22714	0.0	1683	1682	0.0
12	0.05	0.05	0.0	0.25	0.25	0.0	1.48	1.48	0.0	0.0015	0.0015	0.0	24353	24347	0.0	1804	1803	0.0
13	1.41	1.40	0.2	3.79	3.78	0.2	13.05	13.02	0.2	0.0161	0.0161	0.2	148091	147747	0.2	10969	10943	0.2

Table A-8. Verification of MOVES Lite Compared to MOVES: 7 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	0.22	0.22	0.0	0.80	0.80	0.0	8.80	8.80	0.0	0.0033	0.0033	0.0	29954	29954	0.0	2219	2219	0.0
1	0.80	0.80	0.0	2.07	2.07	0.0	19.77	19.77	0.0	0.0060	0.0060	0.0	54910	54906	0.0	4067	4067	0.0
2	0.43	0.43	0.0	1.20	1.20	0.0	12.48	12.48	0.0	0.0041	0.0041	0.0	36720	36720	0.0	2720	2720	0.0
3	0.30	0.30	0.0	0.97	0.97	0.0	10.75	10.74	0.0	0.0040	0.0040	0.0	34958	34953	0.0	2589	2589	0.0
4	0.24	0.24	-0.2	0.87	0.87	-0.2	9.26	9.28	-0.2	0.0036	0.0036	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.20	0.20	-0.1	0.76	0.76	-0.1	8.27	8.28	-0.1	0.0033	0.0033	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.16	0.16	0.1	0.66	0.65	0.1	7.68	7.67	0.1	0.0031	0.0031	0.1	27785	27756	0.1	2058	2056	0.1
7	0.16	0.16	0.1	0.64	0.64	0.1	6.76	6.75	0.1	0.0025	0.0025	0.1	23515	23487	0.1	1742	1740	0.1
8	0.12	0.12	0.0	0.54	0.54	0.0	5.88	5.88	0.0	0.0020	0.0020	0.0	21817	21817	0.0	1616	1616	0.0
9	0.11	0.11	0.0	0.50	0.50	0.0	5.22	5.21	0.0	0.0015	0.0015	0.0	19585	19579	0.0	1451	1450	0.0
10	0.10	0.10	0.0	0.48	0.48	0.0	5.12	5.12	0.0	0.0014	0.0014	0.0	19897	19891	0.0	1474	1473	0.0
11	0.08	0.08	0.0	0.40	0.40	0.0	5.36	5.35	0.0	0.0015	0.0015	0.0	22720	22714	0.0	1683	1682	0.0
12	0.07	0.07	0.0	0.38	0.38	0.0	5.57	5.57	0.0	0.0016	0.0016	0.0	24353	24347	0.0	1804	1803	0.0
13	2.14	2.13	0.2	5.77	5.75	0.2	56.12	55.99	0.2	0.0170	0.0170	0.2	148091	147746	0.2	10969	10943	0.2

Table A-9. Verification of MOVES Lite Compared to MOVES: 9 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	1.04	1.04	0.0	3.88	3.88	0.0	11.81	11.81	0.0	0.6923	0.6923	0.0	29954	29954	0.0	2219	2219	0.0
1	3.87	3.87	0.0	9.99	9.98	0.0	25.63	25.62	0.0	0.7881	0.7880	0.0	54910	54906	0.0	4067	4067	0.0
2	2.06	2.06	0.0	5.77	5.77	0.0	16.36	16.36	0.0	0.7057	0.7057	0.0	36720	36720	0.0	2720	2720	0.0
3	1.47	1.47	0.0	4.70	4.70	0.0	14.39	14.39	0.0	0.8092	0.8091	0.0	34958	34953	0.0	2589	2589	0.0
4	1.17	1.18	-0.2	4.20	4.20	-0.2	12.47	12.50	-0.2	0.7489	0.7502	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.95	0.95	-0.1	3.65	3.66	-0.1	10.92	10.93	-0.1	0.7417	0.7424	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.76	0.76	0.1	3.16	3.16	0.1	10.26	10.25	0.1	0.7405	0.7397	0.1	27785	27756	0.1	2058	2056	0.1
7	0.75	0.75	0.1	3.07	3.07	0.1	9.01	9.00	0.1	0.5463	0.5456	0.1	23515	23487	0.1	1742	1740	0.1
8	0.57	0.57	0.0	2.59	2.59	0.0	7.88	7.88	0.0	0.4688	0.4688	0.0	21817	21817	0.0	1616	1616	0.0
9	0.51	0.51	0.0	2.43	2.43	0.0	7.12	7.11	0.0	0.3439	0.3438	0.0	19585	19579	0.0	1451	1450	0.0
10	0.46	0.46	0.0	2.30	2.30	0.0	7.22	7.22	0.0	0.3228	0.3227	0.0	19897	19891	0.0	1474	1473	0.0
11	0.38	0.38	0.0	1.94	1.94	0.0	7.96	7.96	0.0	0.3772	0.3771	0.0	22720	22714	0.0	1683	1682	0.0
12	0.35	0.35	0.0	1.81	1.81	0.0	8.40	8.39	0.0	0.4086	0.4085	0.0	24353	24347	0.0	1804	1803	0.0
13	10.31	10.28	0.2	27.83	27.77	0.2	73.91	73.74	0.2	1.5875	1.5838	0.2	148091	147746	0.2	10969	10943	0.2

Table A-10. Verification of MOVES Lite Compared to MOVES: 10 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	1.04	1.04	0.0	3.88	3.88	0.0	11.81	11.81	0.0	0.6923	0.6923	0.0	29954	29954	0.0	2219	2219	0.0
1	3.87	3.87	0.0	9.99	9.98	0.0	25.62	25.62	0.0	0.7881	0.7880	0.0	54910	54907	0.0	4067	4067	0.0
2	2.06	2.06	0.0	5.77	5.77	0.0	16.36	16.36	0.0	0.7057	0.7057	0.0	36719	36720	0.0	2720	2720	0.0
3	1.47	1.47	0.0	4.70	4.70	0.0	14.39	14.39	0.0	0.8092	0.8091	0.0	34958	34953	0.0	2589	2589	0.0
4	1.17	1.18	-0.2	4.20	4.20	-0.2	12.47	12.50	-0.2	0.7489	0.7502	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.95	0.95	-0.1	3.65	3.66	-0.1	10.92	10.93	-0.1	0.7417	0.7424	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.76	0.76	0.1	3.16	3.16	0.1	10.26	10.25	0.1	0.7405	0.7397	0.1	27785	27756	0.1	2058	2056	0.1
7	0.75	0.75	0.1	3.07	3.07	0.1	9.01	9.00	0.1	0.5463	0.5457	0.1	23515	23487	0.1	1742	1740	0.1
8	0.57	0.57	0.0	2.59	2.59	0.0	7.88	7.88	0.0	0.4688	0.4688	0.0	21817	21817	0.0	1616	1616	0.0
9	0.51	0.51	0.0	2.43	2.43	0.0	7.12	7.11	0.0	0.3439	0.3438	0.0	19585	19579	0.0	1451	1450	0.0
10	0.46	0.46	0.0	2.30	2.30	0.0	7.22	7.22	0.0	0.3228	0.3227	0.0	19897	19891	0.0	1474	1473	0.0
11	0.38	0.38	0.0	1.94	1.94	0.0	7.96	7.96	0.0	0.3772	0.3771	0.0	22720	22714	0.0	1683	1682	0.0
12	0.35	0.35	0.0	1.81	1.81	0.0	8.40	8.39	0.0	0.4086	0.4085	0.0	24353	24347	0.0	1804	1803	0.0
13	10.31	10.28	0.2	27.83	27.77	0.2	73.91	73.74	0.2	1.5875	1.5838	0.2	148090	147746	0.2	10969	10943	0.2

Table A-11. Verification of MOVES Lite Compared to MOVES: 15 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	1.13	1.13	0.0	8.56	8.56	0.0	20.71	20.71	0.0	0.7661	0.7661	0.0	29954	29954	0.0	2219	2219	0.0
1	3.47	3.47	0.0	21.19	21.19	0.0	42.04	42.04	0.0	0.8720	0.8719	0.0	54910	54907	0.0	4067	4067	0.0
2	1.90	1.90	0.0	12.96	12.96	0.0	26.35	26.35	0.0	0.7808	0.7808	0.0	36720	36720	0.0	2720	2720	0.0
3	1.42	1.42	0.0	10.81	10.80	0.0	23.90	23.90	0.0	0.8954	0.8953	0.0	34958	34953	0.0	2589	2589	0.0
4	1.17	1.17	-0.2	8.86	8.88	-0.2	21.12	21.16	-0.2	0.8287	0.8302	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.95	0.95	-0.1	7.86	7.86	-0.1	18.79	18.80	-0.1	0.8207	0.8215	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.84	0.84	0.1	7.10	7.10	0.1	18.65	18.63	0.1	0.8194	0.8185	0.1	27785	27756	0.1	2058	2056	0.1
7	0.83	0.83	0.1	6.36	6.35	0.1	16.46	16.44	0.1	0.6045	0.6038	0.1	23515	23487	0.1	1742	1740	0.1
8	0.77	0.77	0.0	5.52	5.52	0.0	15.57	15.57	0.0	0.5187	0.5187	0.0	21817	21817	0.0	1616	1616	0.0
9	0.76	0.76	0.0	4.95	4.95	0.0	14.74	14.74	0.0	0.3805	0.3804	0.0	19585	19579	0.0	1451	1450	0.0
10	0.73	0.73	0.0	4.82	4.82	0.0	15.55	15.55	0.0	0.3572	0.3571	0.0	19897	19891	0.0	1474	1473	0.0
11	0.67	0.67	0.0	4.80	4.80	0.0	17.71	17.70	0.0	0.4174	0.4173	0.0	22720	22714	0.0	1683	1682	0.0
12	0.67	0.67	0.0	4.91	4.91	0.0	18.80	18.80	0.0	0.4521	0.4520	0.0	24353	24347	0.0	1804	1803	0.0
13	10.43	10.41	0.2	49.07	48.96	0.2	130.04	129.74	0.2	1.7566	1.7525	0.2	148091	147747	0.2	10969	10943	0.2

Table A-12. Verification of MOVES Lite Compared to MOVES: 30 Year Old Long Haul Trucks

Cycle ID	HC			CO			NO_x			$PM_{2.5}$			Energy			CO_2		
	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff	MOVES-Lite (KJ/mi)	MOVES (KJ/mi)	% diff	MOVES Lite (g/mi)	MOVES (g/mi)	% diff
0	1.13	1.13	0.0	8.56	8.56	0.0	41.40	41.40	0.0	2.4921	2.4921	0.0	29954	29954	0.0	2219	2219	0.0
1	3.47	3.47	0.0	21.19	21.19	0.0	77.91	77.90	0.0	2.4194	2.4192	0.0	54910	54907	0.0	4067	4067	0.0
2	1.90	1.90	0.0	12.96	12.96	0.0	50.37	50.37	0.0	2.3438	2.3439	0.0	36720	36720	0.0	2720	2720	0.0
3	1.42	1.42	0.0	10.81	10.80	0.0	47.78	47.77	0.0	2.7267	2.7263	0.0	34958	34953	0.0	2589	2589	0.0
4	1.17	1.17	-0.2	8.86	8.88	-0.2	43.43	43.51	-0.2	2.4809	2.4854	-0.2	30661	30717	-0.2	2271	2275	-0.2
5	0.95	0.95	-0.1	7.86	7.86	-0.1	40.32	40.36	-0.1	2.5085	2.5107	-0.1	28345	28370	-0.1	2099	2101	-0.1
6	0.84	0.84	0.1	7.10	7.10	0.1	40.01	39.97	0.1	2.5339	2.5313	0.1	27785	27756	0.1	2058	2056	0.1
7	0.83	0.83	0.1	6.36	6.35	0.1	34.25	34.21	0.1	1.9930	1.9906	0.1	23515	23487	0.1	1742	1740	0.1
8	0.77	0.77	0.0	5.52	5.52	0.0	31.69	31.69	0.0	1.9213	1.9213	0.0	21817	21817	0.0	1616	1616	0.0
9	0.76	0.76	0.0	4.95	4.95	0.0	28.90	28.89	0.0	1.6634	1.6629	0.0	19585	19579	0.0	1451	1450	0.0
10	0.73	0.73	0.0	4.82	4.82	0.0	30.10	30.09	0.0	1.6570	1.6565	0.0	19897	19890	0.0	1474	1473	0.0
11	0.67	0.67	0.0	4.80	4.80	0.0	35.14	35.13	0.0	1.8977	1.8972	0.0	22720	22714	0.0	1683	1682	0.0
12	0.67	0.67	0.0	4.91	4.91	0.0	37.68	37.67	0.0	2.0466	2.0461	0.0	24353	24347	0.0	1804	1803	0.0
13	10.43	10.41	0.2	49.07	48.96	0.2	230.45	229.92	0.2	3.2018	3.1944	0.2	148091	147747	0.2	10969	10943	0.2