USEPA's MOVES Model
Motor Vehicle Emission Simulator

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USEPA's MOVES Model
Motor Vehicle Emissions Simulator

- Developed by the U.S. EPA over 10+ years
  - Incorporates findings from university research efforts
  - UC Riverside, Georgia Tech, NC State, and MIT
- Calculates energy as a function of on-road operating conditions and environmental factors
- Calculates emissions as a function of energy use
- Energy and emission rates that can be applied at any scale
  - Macroscale, mesoscale, microscale
- Must be used in all federal regulatory analyses

https://www.epa.gov/moves/moves-onroad-technical-reports

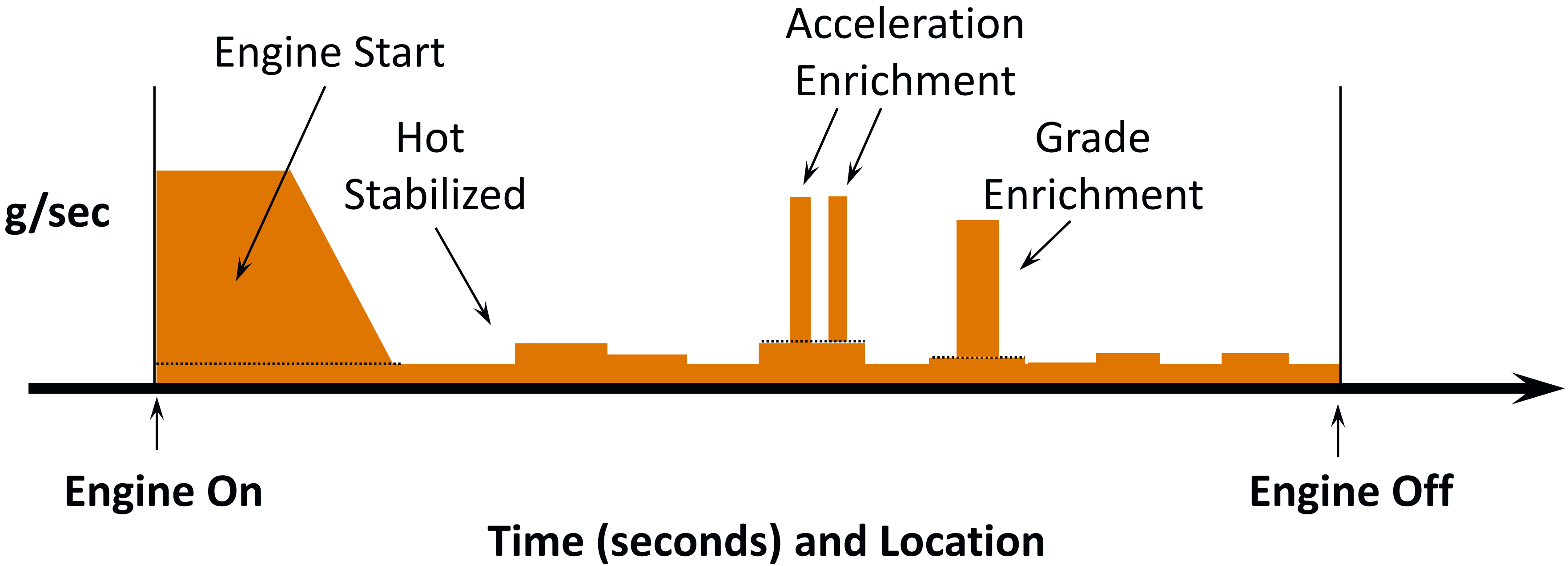
MOVES Applications

- National greenhouse gas inventories
- Regional air quality planning (CAA State Implementation Plans)
  - Generate regional emissions inventories
  - Assess emission changes over time
  - Assess mobile source emission reduction strategies
- Transportation planning
  - Assess impacts of plans, programs, and projects
  - Project-level corridor and intersection assessments
- Transportation and air quality conformity regulations
- Microscale air quality impact assessment for environmental impact statements (EISs) under NEPA

MOVES Incorporates More and Better Data and Improved Analyses

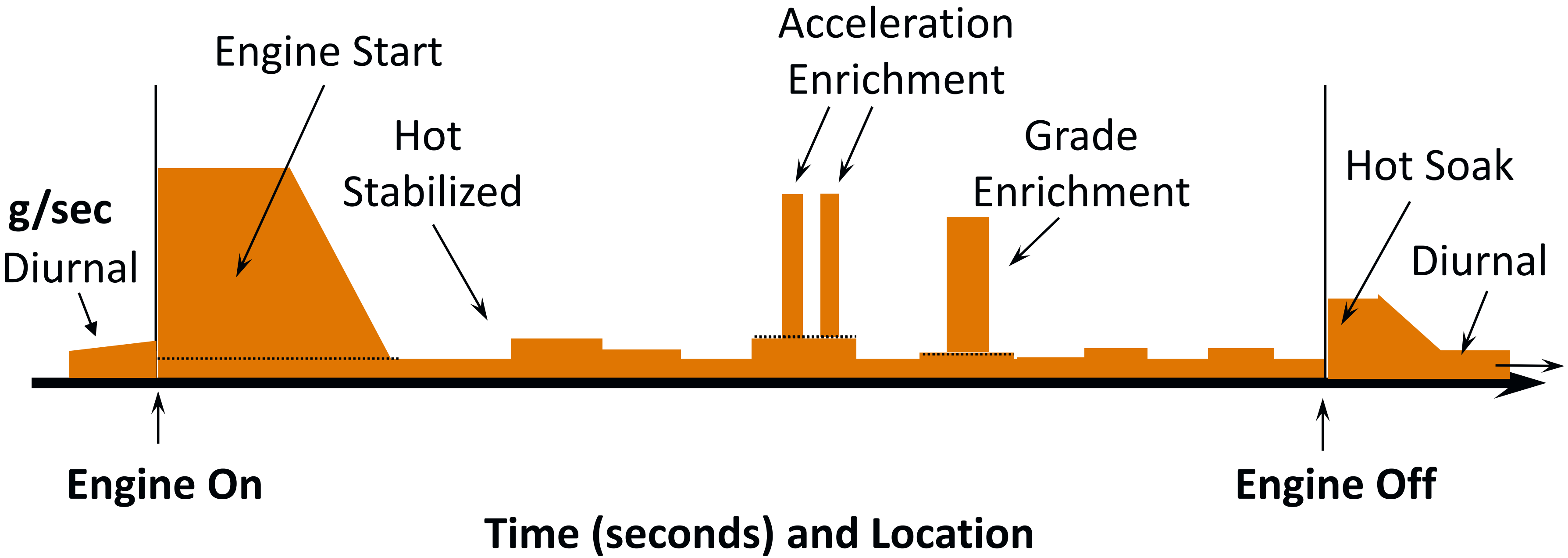
- Portable emissions monitoring systems (PEMS) for instantaneous second-by-second data
    - GPS data link PEMS data to vehicle location and speed/acceleration
    - Onboard diagnostics systems (OBD) provided engine and vehicle operation information
- Remote sensing data and I/M test data
- Statistical modeling of relationships
    - Emissions by operating condition (binning approach)

Carbon Monoxide (CO) Emission Rates for a Hypothetical Trip



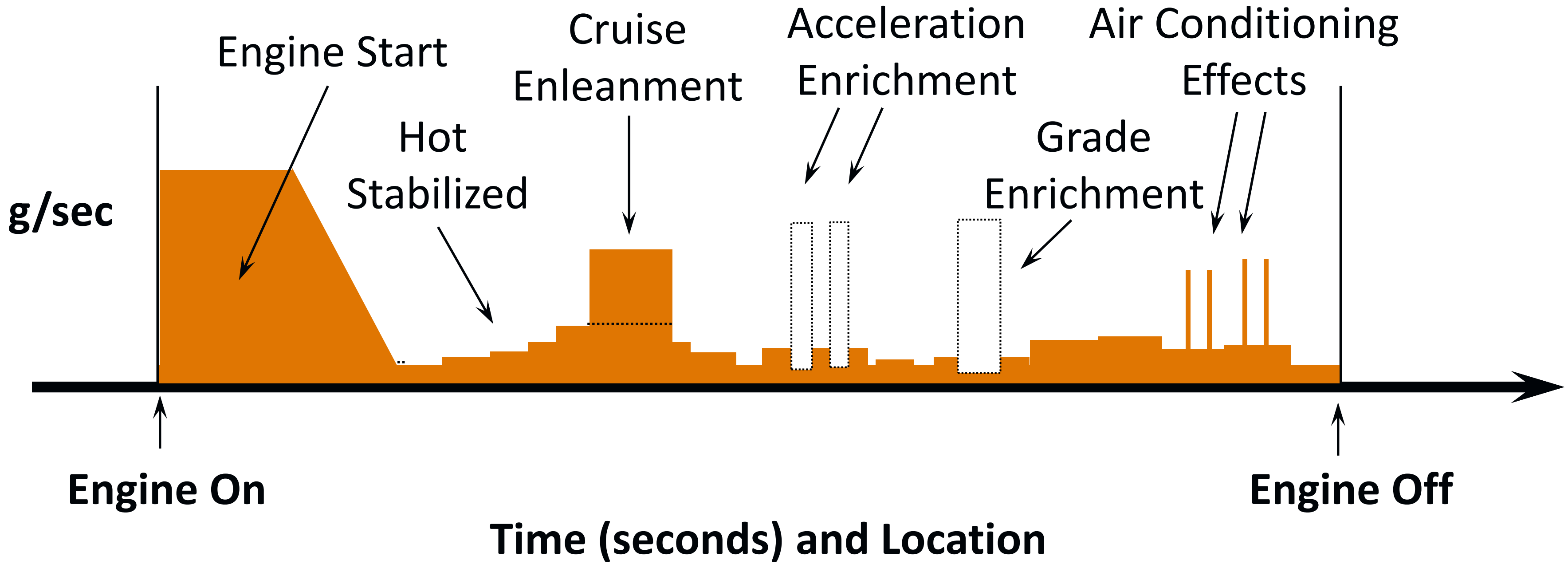
Source: Bachman and Guensler, 1996

Hydrocarbon (HC) Emission Rates for a Hypothetical Trip



Source: Bachman and Guensler, 1996

Oxides of Nitrogen (NO_x) Emission Rates for a Hypothetical Trip



Source: Bachman and Guensler, 1996

Processes Modeled in MOVES

- On-road energy use and emissions production
  - Running exhaust
  - Crankcase running exhaust
  - Brake wear and tire wear
- Elevated engine start emissions (warm-up)
- Extended idle
- Running evaporative losses
- Diurnal evaporative losses
- Vapor emissions from refueling and spillage

MOVES Modeling Approach

- Emissions are defined as a function of speed and vehicle-specific power (VSP), to reflect speed-acceleration impacts on engine work
  - Driving cycles (speed-acceleration activity) can be decomposed into operating mode bins and modeled as a function of operating time spent in each VSP bin
- Run separate analyses for any combination of: calendar year, fuel specification, I/M program, environmental conditions, etc.

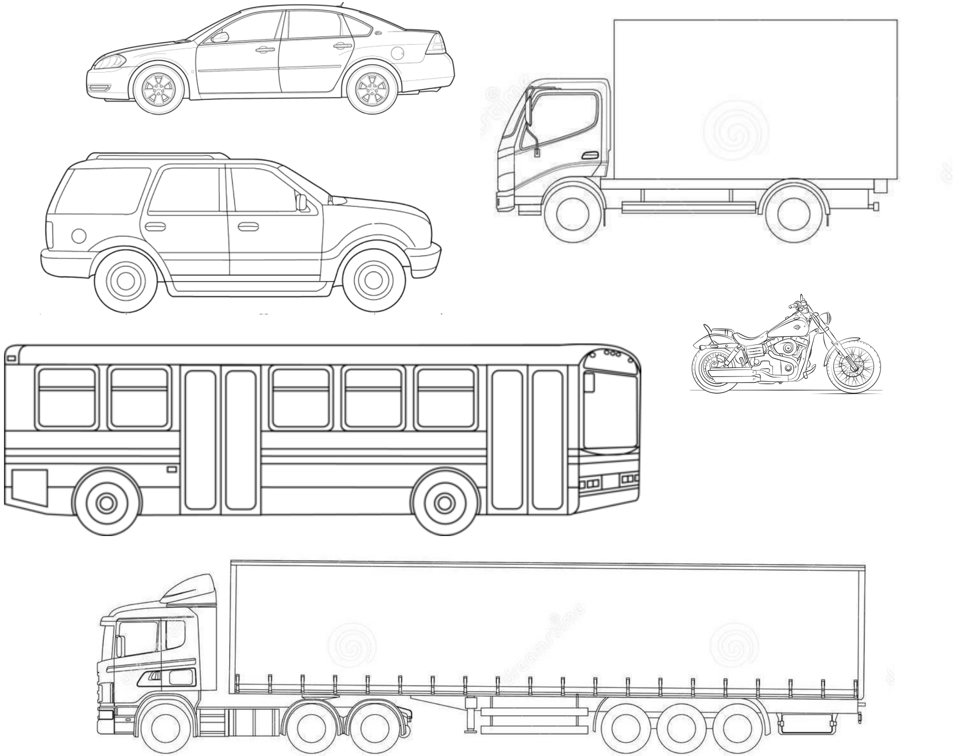
MOVES On-road Energy and Emission Modeling

MOVES Energy Use and Emissions Factors to Consider

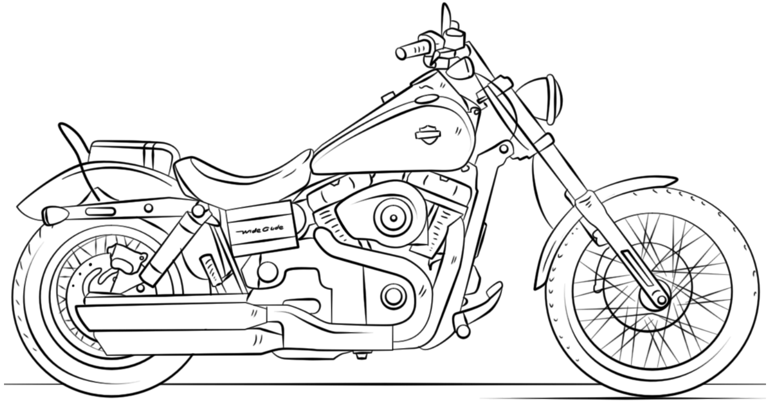
- Onroad fleet (vehicle types and age)
  - Varies by location and time of day
  - Depends on calendar year of evaluation (2020 vs. 2040)
- On-road operating conditions
  - Varies by location and time of day (and vehicle type)
- Environmental conditions (temperature, humidity, etc.)
- Fuel used by the fleet
- Regulatory programs in place to control emissions
  - Inspection and maintenance (I/M programs)

Fleet Composition
MOVES Source Types

Source Type Name	Source Type ID
Motorcycle	11
Passenger Car	21
Passenger Truck	31
Light Commercial Truck	32
Intercity Bus	41
Transit Bus	42
School Bus	43
Refuse Truck	51
Single-Unit Short Haul Truck	52
Single-Unit Long Haul Truck	53
Motor Home	54
Combination Short Haul Truck	61
Combination Long Haul Truck	62



Motorcycle
Source Type 11



Source: http://www.supercoloring.com/coloring-pages/harley-davidson-motorcycle

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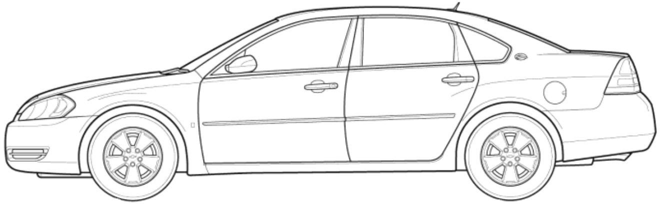
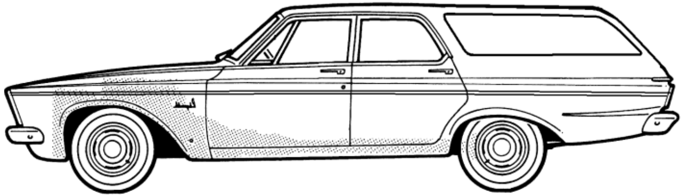
Passenger Car Source Type 21

https://www.nadaguides.com/Cars/2018/Volvo/V90/T5-FWD-Inscription/Pictures

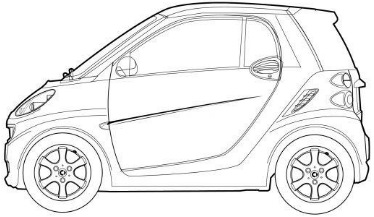
https://www.nadaguides.com/Cars/2010/smart/FORTWO-3-Cyl/Coupe-2D-Passion/Pictures



https://getoutlines.com/blueprints/847/2007-chevrolet-impala-lt-sedan-blueprints?utm_source=cbinfo&utm_medium=cpm&utm_campaign=cbinfo&utm_content=button&id=0&page=1&search=&section=administrator&status=0&order=0&author=0&contact=0&category_id=0&filter%5Bcategory_id%5D=0&filter%5Bmake_id%5D=0&filter%5Bset_id%5D=0&make_id=0&report_id=0&update_count=0&days=0&want_pay=0



https://www.the-blueprints.com/blueprints/cars/plymouth/63476/view/plymouth_belvedere_station_wagon_1963/



https://cartype.com/pages/4507/car_line_art

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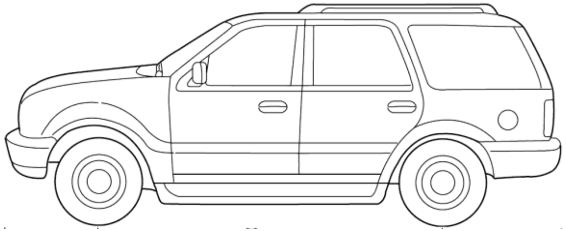
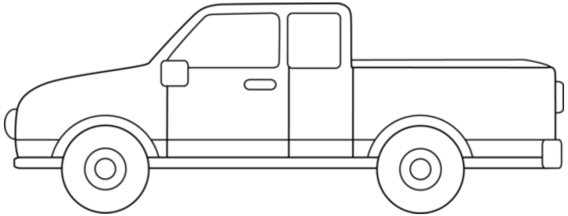
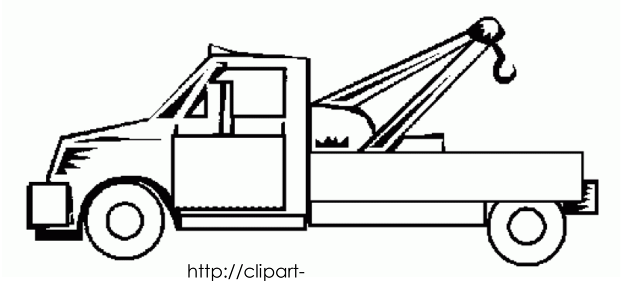
Passenger Truck Source Type 31

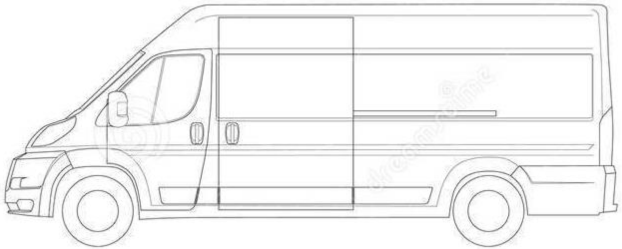
https://www.knapheide.com/mechanics-trucks/kmt1-p37

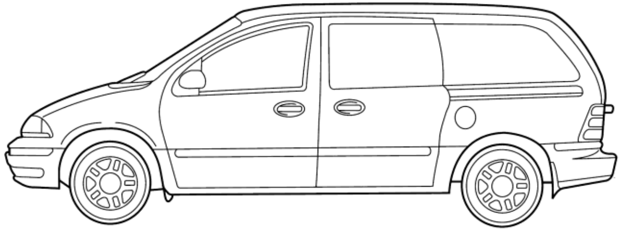






http://clipart-library.com/clipart/BiaA8L6MT.htm





http://www.supercoloring.com/silhouettes/pickup-truck

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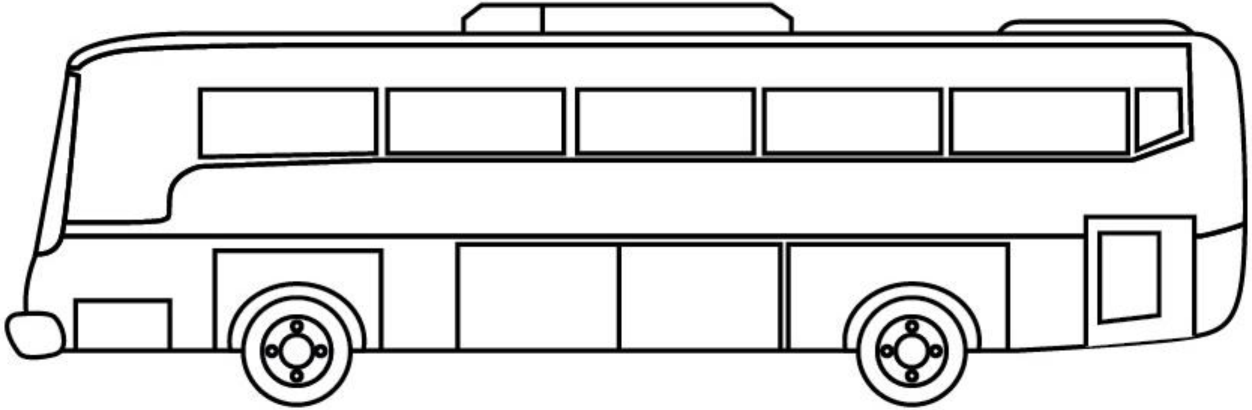
Light Commercial Truck Source Type 32

https://www.theonion.com/study-finds-87-of-knowledge-about-nation-comes-from-si-1826298908

https://www.travelandleisure.com/travel-tips/ground-transportation/why-ups-trucks-dont-turn-left

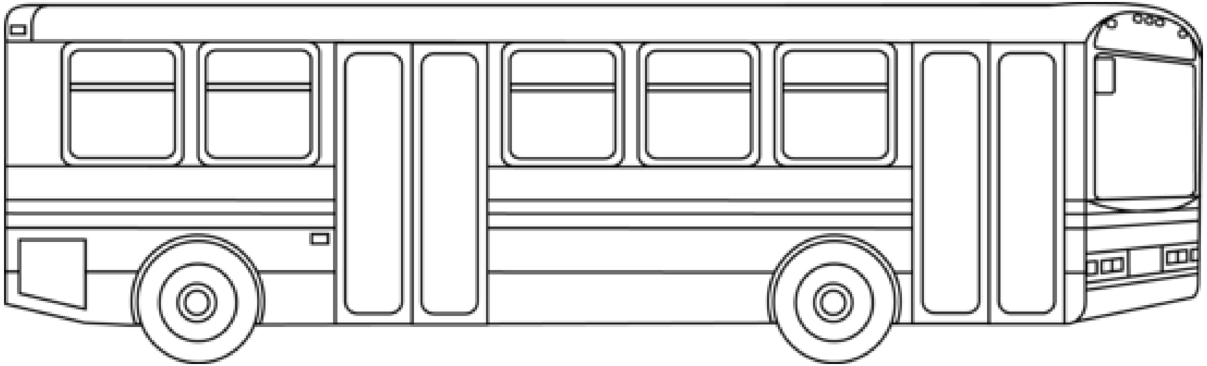
https://www.glassdoor.com/Photos/US-Postal-Service-Office-Photos-IMG420.htm

Intercity Bus
Source Type 41



Source: https://www.gograph.com/

Transit Bus
Source Type 42



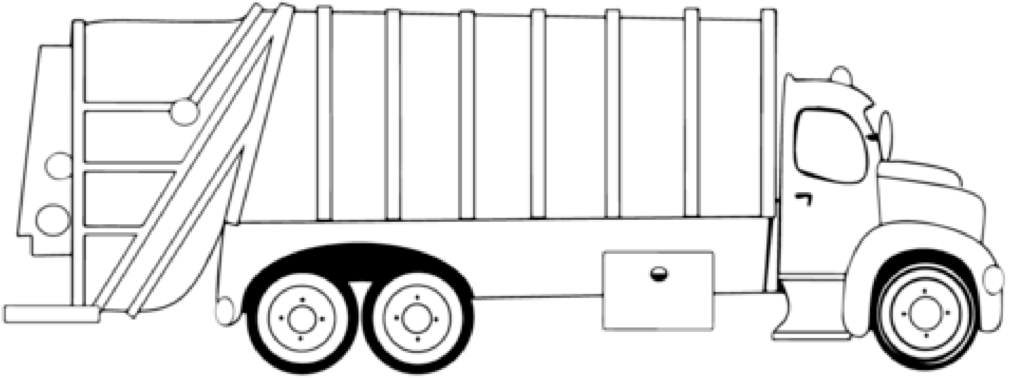
Source: https://www.gograph.com/

School Bus
Source Type 43

https://www.dart.org/riding/paratransit.asp

Source: https://www.gograph.com/

Refuse Truck
Source Type 51



Source: http://www.supercoloring.com/coloring-pages/garbage-truck

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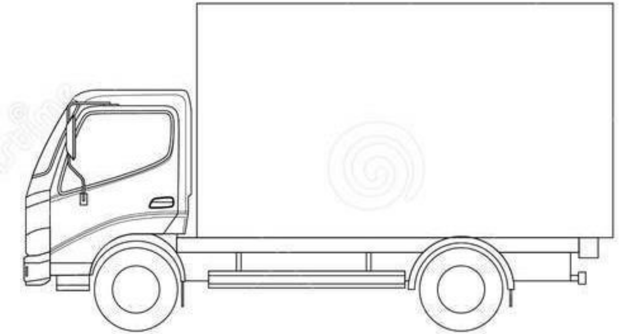
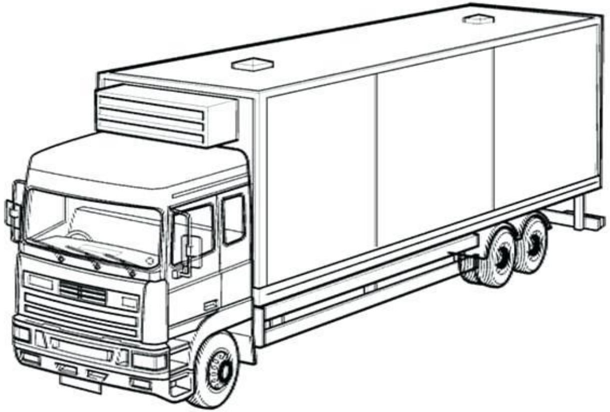
Single Unit Truck (Short-haul/Long-haul) Source Type 52/53

http://rock-cafe.info/posts/transport-truck-side-view-7472616e73706f7274.html

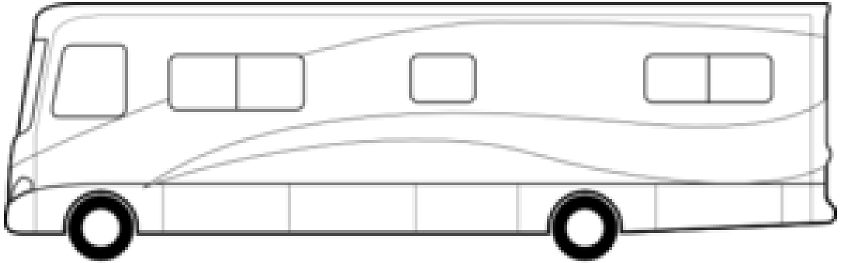


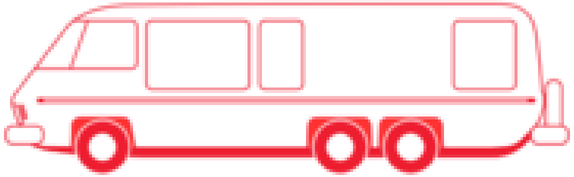
Source: https://www.shutterstock.com/zh/search/tractor+trailer+truck



http://benneedham.info/printable-truck-coloring-pages/

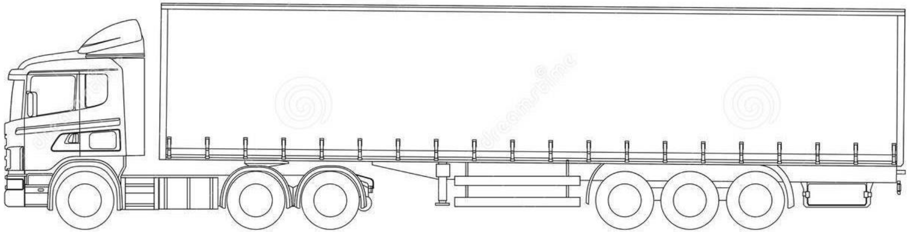
Motor Home
Source Type 54

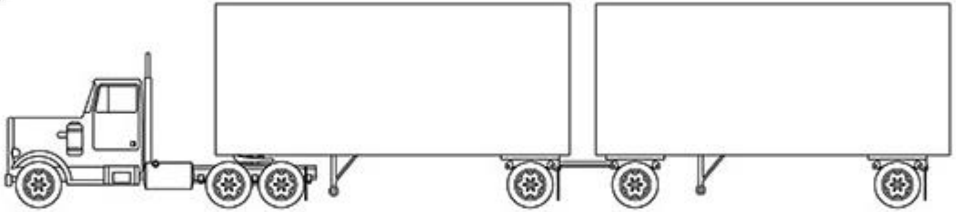




Source: https://www.gograph.com/

Combination Trucks (Short-haul/Long-haul)
Source Type 61/62

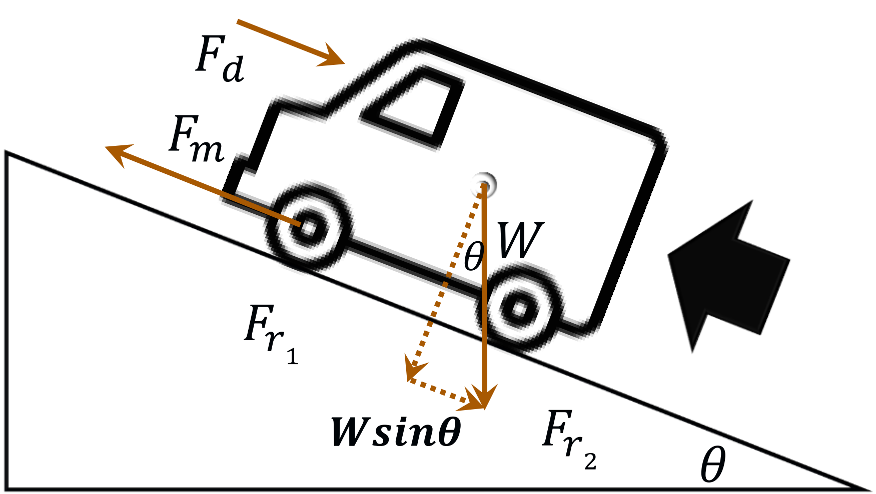




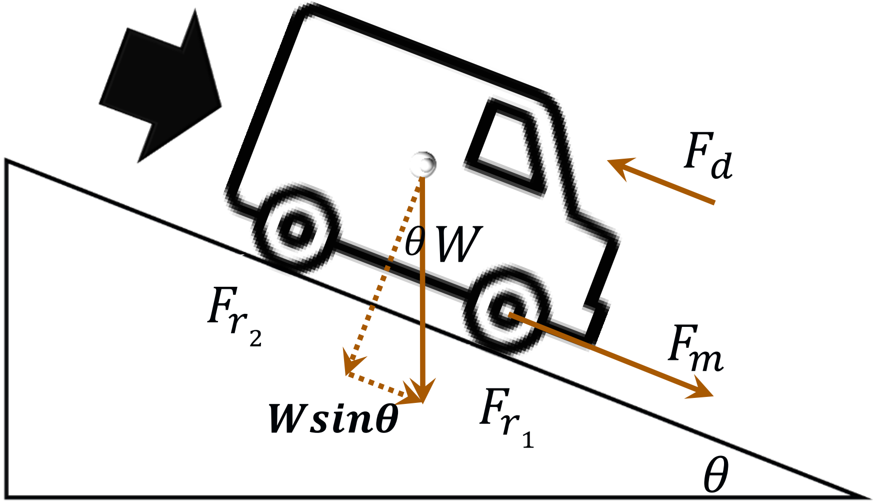
Source: https://ayoqq.org/explore/outline-drawing-semi-truck/
Source: https://cad-block.com/205-trucks-set.html

Force and Engine Load

Driving uphill (***Wsinθ***)
increases required engine work



Driving downhill (***Wsinθ***)
decreases required engine work



F_m = Motive force
F_d = Aerodynamic drag
F_{r1}, F_{r2} = Rolling friction
W = Gravity
θ = Road grade
$\boldsymbol{Wsin\theta}$ = component gravitational force in driving direction

MOVES Modeling

$$VSP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(a + g * \sin\theta)v$$

- **Modeling is performed for each vehicle class**
- **Emissions are defined as a function of speed and vehicle-specific power (VSP) to account for the impact of speed and acceleration on energy and emissions**
- **MOVES translates model inputs into this VSP framework, processes the inputs, and translates results back into user-required outputs**
- **Road grade (θ) can be explicitly handled in MOVES**

Vehicle-Specific Power

- Units of kW/tonne (power to weight ratio)
- Power demand is a function of vehicle characteristics, speed, and acceleration
- Emissions are a function of the energy (work) required to move the vehicle, which depends upon power demand, weight of vehicle, and onroad operating conditions
- MOVES emission rates are established by VSP bin for each vehicle source type

Vehicle Specific Power (VSP) Equation Coefficients Vary by Source Type

$$VSP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(a + g * \sin\theta)v$$

- **VSP = Vehicle-specific power (kW/tonne)**
- **M = Fixed mass factor (tonnes) for the vehicle type (sourceType)**
- **m = Source mass (tonnes), m equals M for LDVs**
- **A = Rolling resistance (kW/meter/second)**
- **B = Rotational resistance (kW-sec^2/meter^2)**
- **C = Drag coefficient kW-second^3/meter^3**
- **v = Vehicle velocity (meters/sec)**
- **a = Vehicle acceleration (meters/second^2)**
- **g = Gravitational acceleration (9.8 m/second^2)**
- **θ = Road grade angle (radians or degrees, as needed)**

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Scaled Tractive Power (STP) Equation Coefficients vary by Source Type

$$STP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(a + g * \sin\theta)v$$

- **STP = Scaled tractive power (kW/tonne)**
- **M = Fixed mass factor (tonnes) for the vehicle type (sourceType)**
- **m = Source mass (tonnes)**
- **A = Rolling resistance (kW/meter/second)**
- **B = Rotational resistance (kW-sec^2/meter^2)**
- **C = Drag coefficient kW-second^3/meter^3**
- **v = Vehicle velocity (meters/sec)**
- **a = Vehicle acceleration (meters/second^2)**
- **g = Gravitational acceleration (9.8 m/second^2)**
- **θ = Road grade angle (radians or degrees, as needed)**

23 MOVES Operating Mode Bins

Operating Mode ID	Operating Mode	Scaled Tractive Power	Vehicle Speed	Vehicle Acceleration
	Description	(VSP_t, skW)	(v_t, mph)	(a, mph/second)
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		$-1.0 \leq v_t < 1.0$	Any
11	Coast	$VSP_t < 0$	$0 \leq v_t < 25$	Any
12	Cruise/Acceleration	$0 \leq VSP_t < 3$	$0 \leq v_t < 25$	Any
13	Cruise/Acceleration	$3 \leq VSP_t < 6$	$0 \leq v_t < 25$	Any
14	Cruise/Acceleration	$6 \leq VSP_t < 9$	$0 \leq v_t < 25$	Any
15	Cruise/Acceleration	$9 \leq VSP_t < 12$	$0 \leq v_t < 25$	Any
16	Cruise/Acceleration	$12 \leq VSP_t$	$0 \leq v_t < 25$	Any
21	Coast	$VSP_t < 0$	$25 \leq v_t < 50$	Any
22	Cruise/Acceleration	$0 \leq VSP_t < 3$	$25 \leq v_t < 50$	Any
23	Cruise/Acceleration	$3 \leq VSP_t < 6$	$25 \leq v_t < 50$	Any
24	Cruise/Acceleration	$6 \leq VSP_t < 9$	$25 \leq v_t < 50$	Any
25	Cruise/Acceleration	$9 \leq VSP_t < 12$	$25 \leq v_t < 50$	Any
27	Cruise/Acceleration	$12 \leq VSP_t < 18$	$25 \leq v_t < 50$	Any
28	Cruise/Acceleration	$18 \leq VSP_t < 24$	$25 \leq v_t < 50$	Any
29	Cruise/Acceleration	$24 \leq VSP_t < 30$	$25 \leq v_t < 50$	Any
30	Cruise/Acceleration	$30 \leq VSP_t$	$25 \leq v_t < 50$	Any
33	Cruise/Acceleration	$VSP_t < 6$	$50 \leq v_t$	Any
35	Cruise/Acceleration	$6 \leq VSP_t < 12$	$50 \leq v_t$	Any
37	Cruise/Acceleration	$12 \leq VSP_t < 18$	$50 \leq v_t$	Any
38	Cruise/Acceleration	$18 \leq VSP_t < 24$	$50 \leq v_t$	Any
39	Cruise/Acceleration	$24 \leq VSP_t < 30$	$50 \leq v_t$	Any
40	Cruise/Acceleration	$30 \leq VSP_t$	$50 \leq v_t$	Any

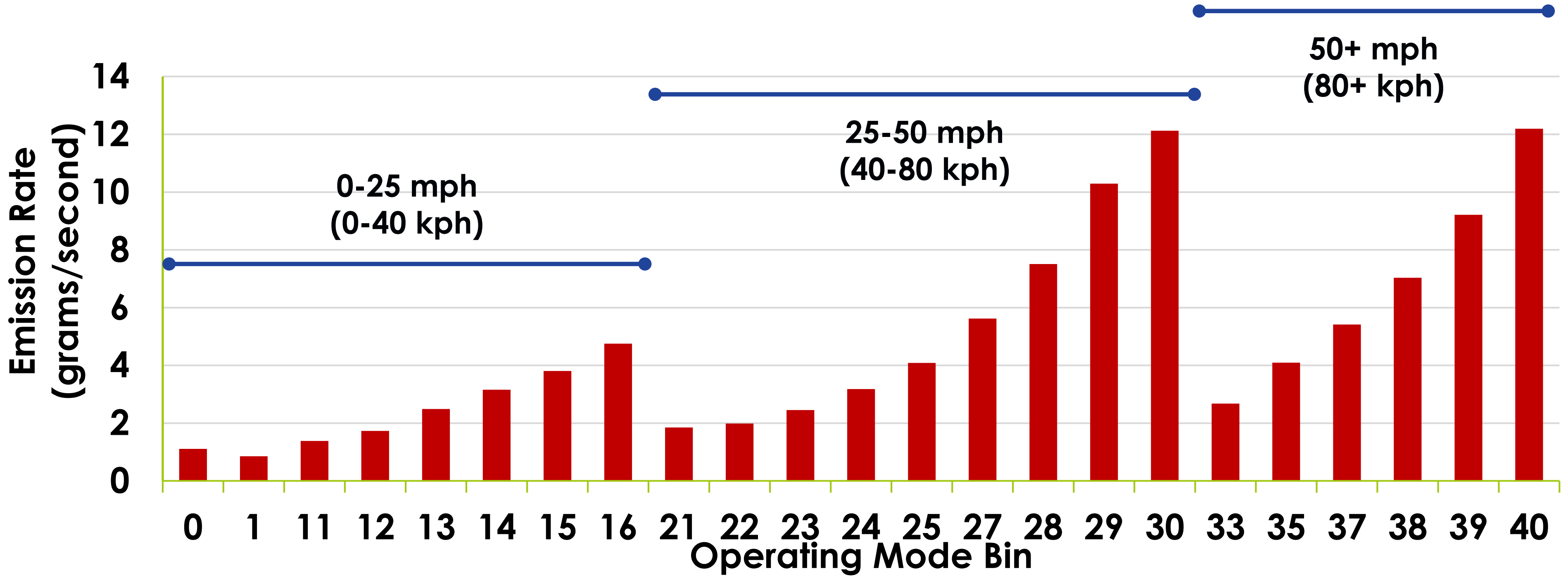
Braking Mode

Idle Mode

VSP Modes for three speed regimes:

0-25 mph
25-50 mph
50+ mph

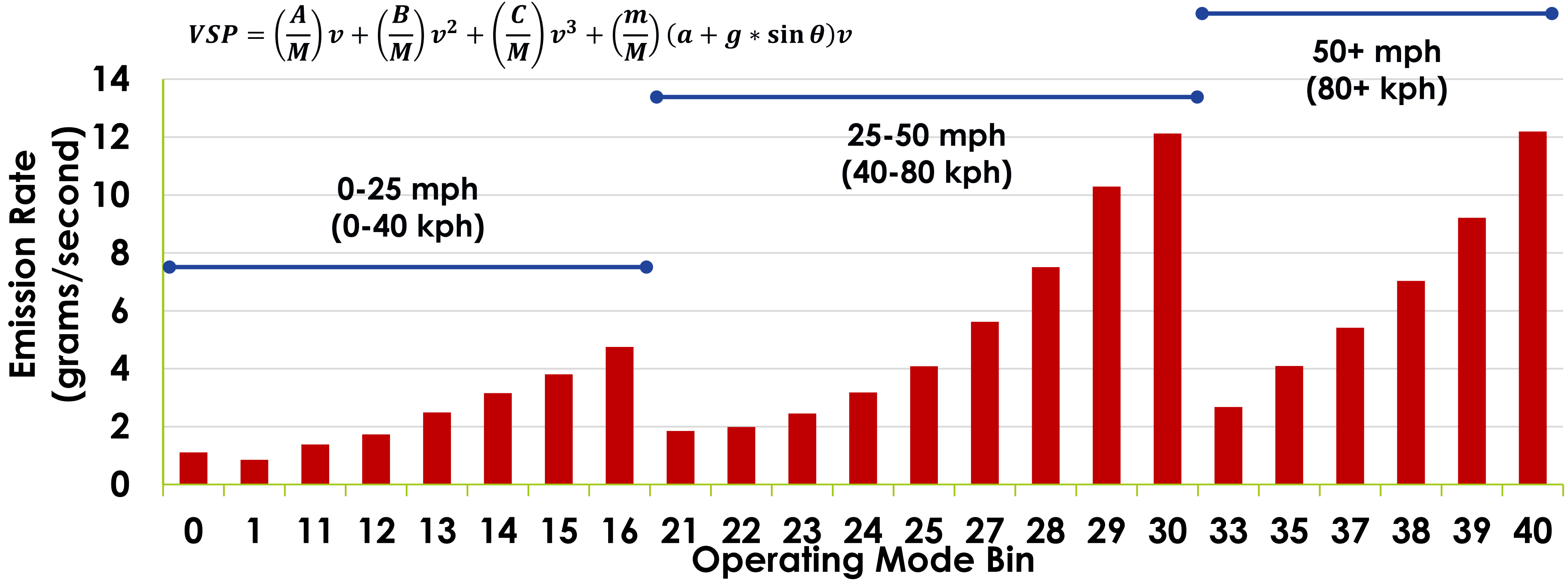
Example CO_2 Emission Rates by OpMode Bin for Passenger Trucks (2016MY in 2016)



23 operating mode bins
0 = braking, 1 = idle, 11 = coast, 21 = coast

Example CO_2 Emission Rates by OpMode Bin for Passenger Trucks (2016MY in 2016)

$$VSP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(a + g * \sin\theta)v$$



23 operating mode bins

0 = braking, 1 = idle, 11 = coast, 21 = coast

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MOVES Modeling Steps

- Estimate total vehicle activity
  - (e.g., hours of vehicle operation)
- Distribute activity by vehicle sub-fleets (source type, age)
- Distribute sub-fleet activity by operating condition
  - Operating mode (op-mode) bins
- Get MOVES emission rates (g/sec):
  - For source type, model year, and op-mode bin
  - For given temperature, humidity, fuel, etc.
- Multiply activity per op-mode bin by applicable bin emission rates for that sub-fleet

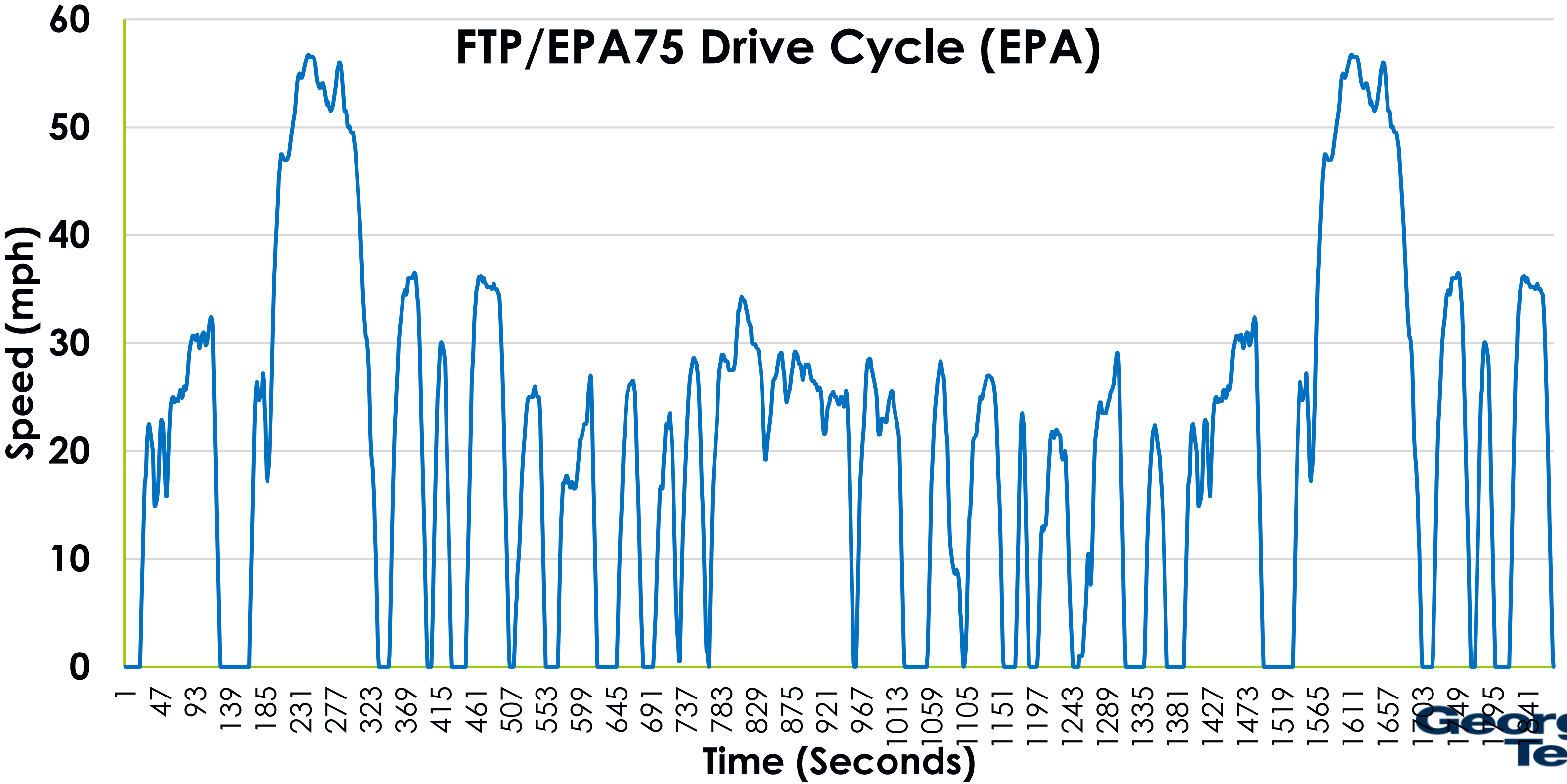
MOVES On-Road Fleet Emission Rates

- MOVES weights emission rates by source type (ST), model year (MY), and operating mode (OM) bin activity to generate the fleet emission rate for existing conditions

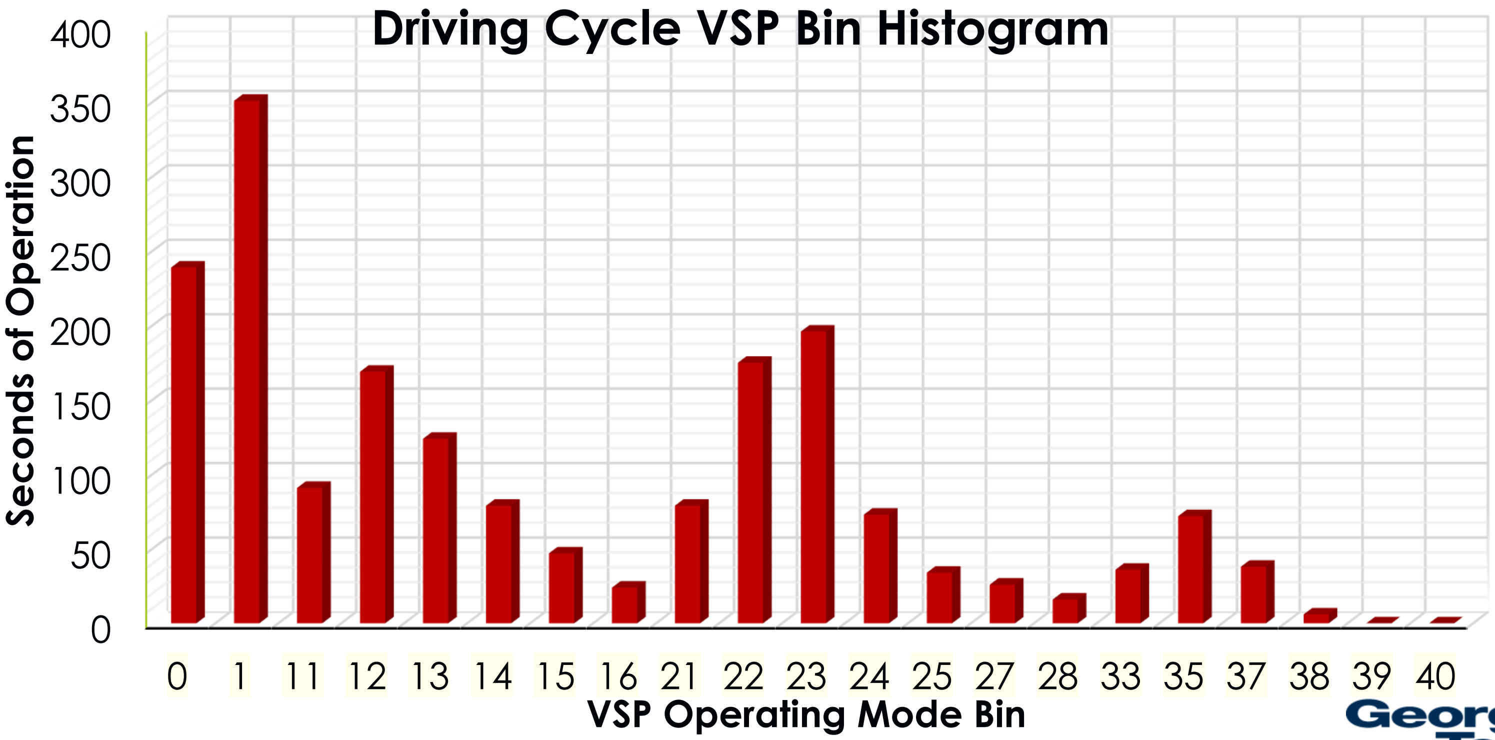
$$\mathrm{ER}_{\mathrm{Fleet}} = \sum_{\mathrm{ST}} \sum_{\mathrm{MY}} \sum_{\mathrm{OM(SF)}} \mathrm{ST\%} \times \mathrm{MY\%}_{\mathrm{ST}} \times \mathrm{OM(SF)\%}_{\mathrm{ST,MY}} \times \mathrm{ER}_{\mathrm{ST,MY,OM(SF)}}$$

- Can use average speed and facility type (SF) instead of operating mode bin distribution (MOVES assigns bins)
- MOVES output is the fleet emission rate (g/sec, g/hour, g/mile)

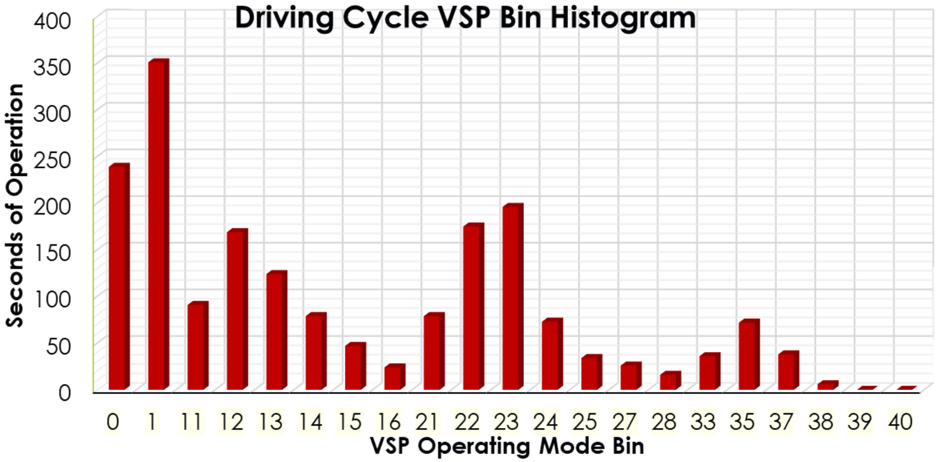
Application of MOVES to Second-by-Second Data



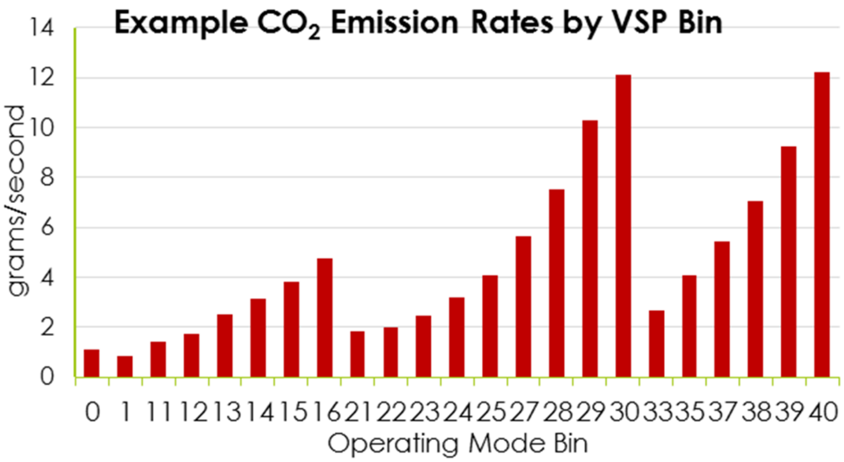
Drive Cycle to OpMode Bin Distribution



Multiply Bin Activity by Bin-Based Energy Use and Emissions Rates



X



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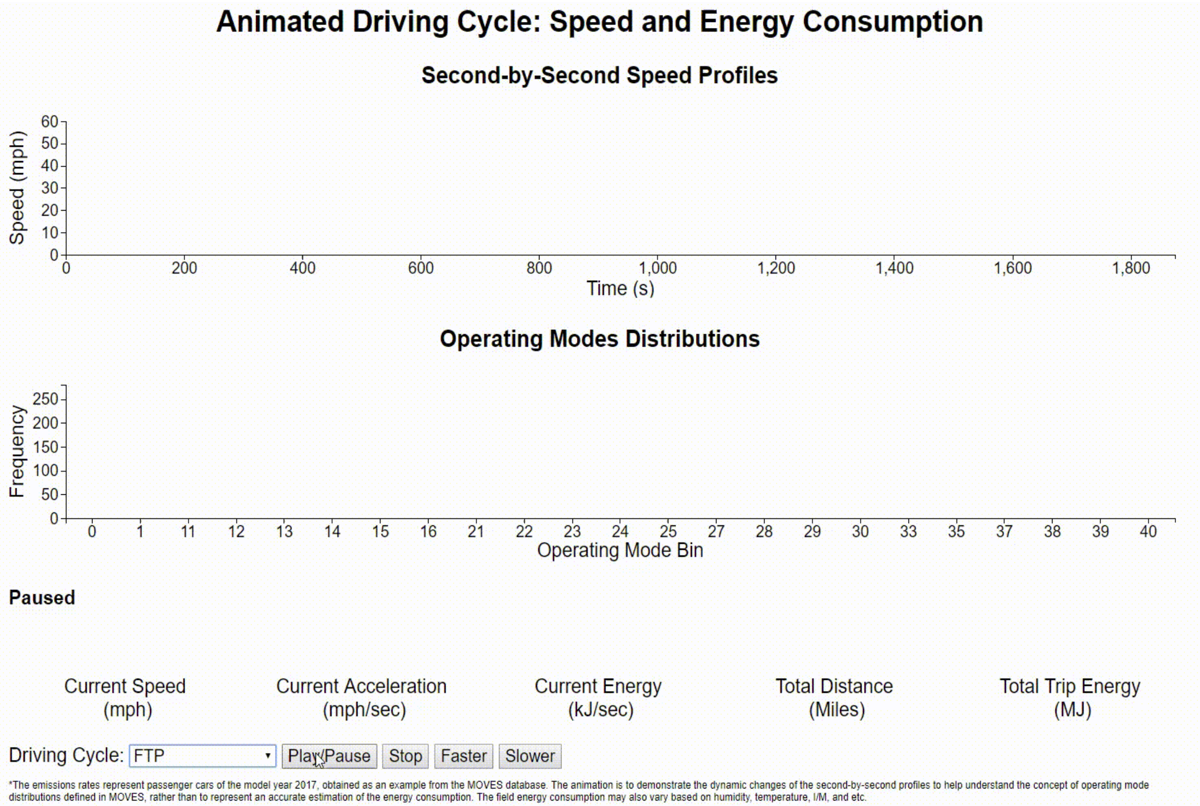
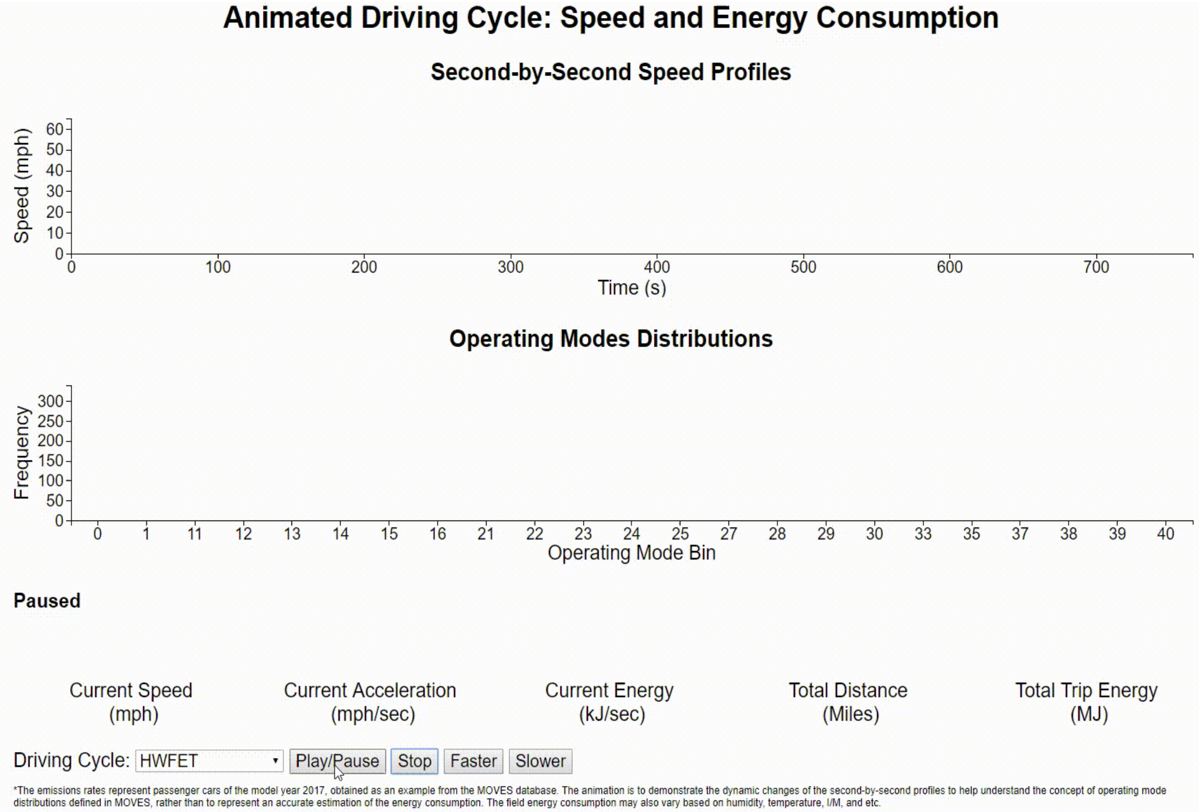
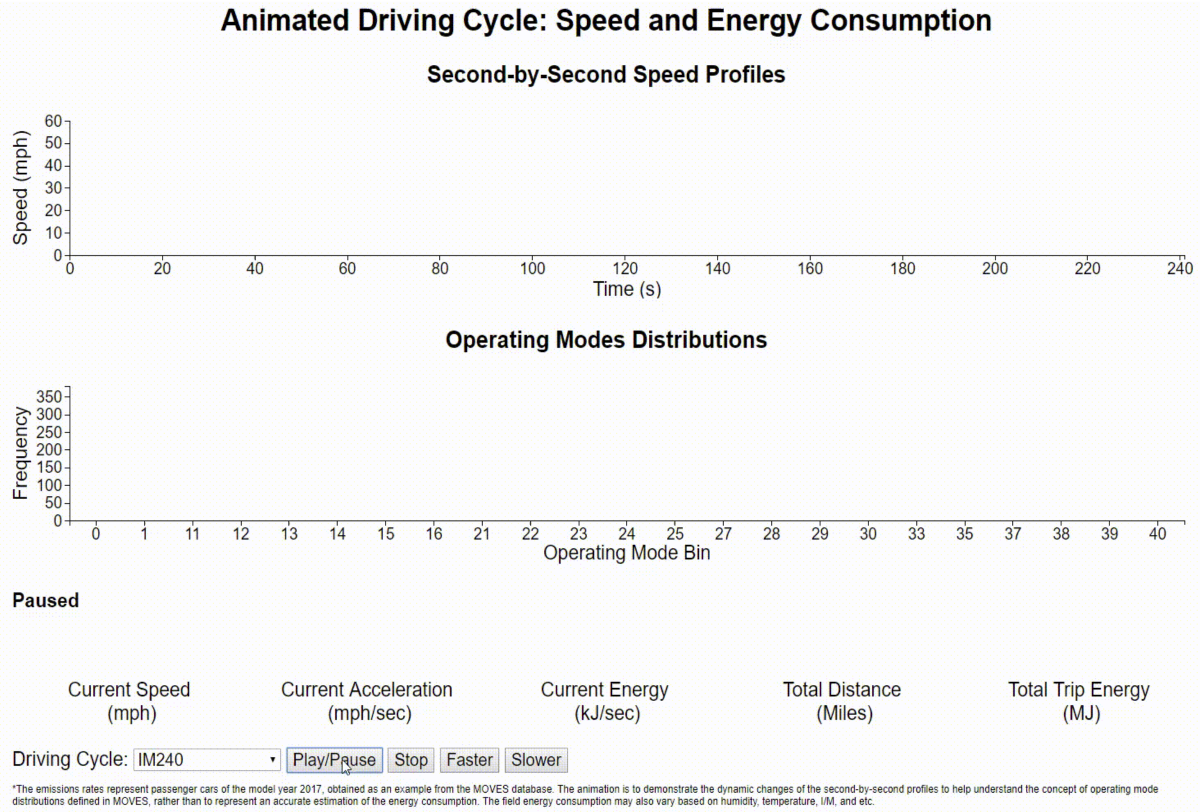
FTP Driving Cycle



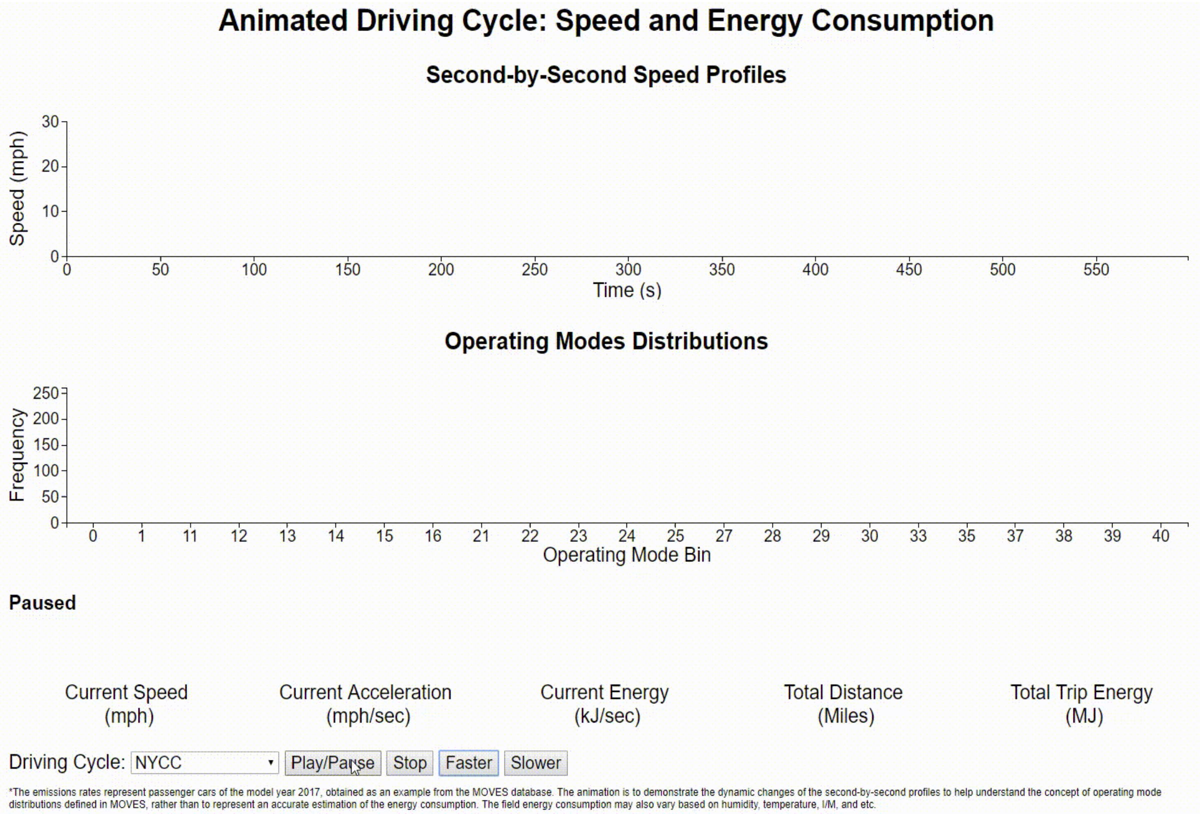
HFET Driving Cycle



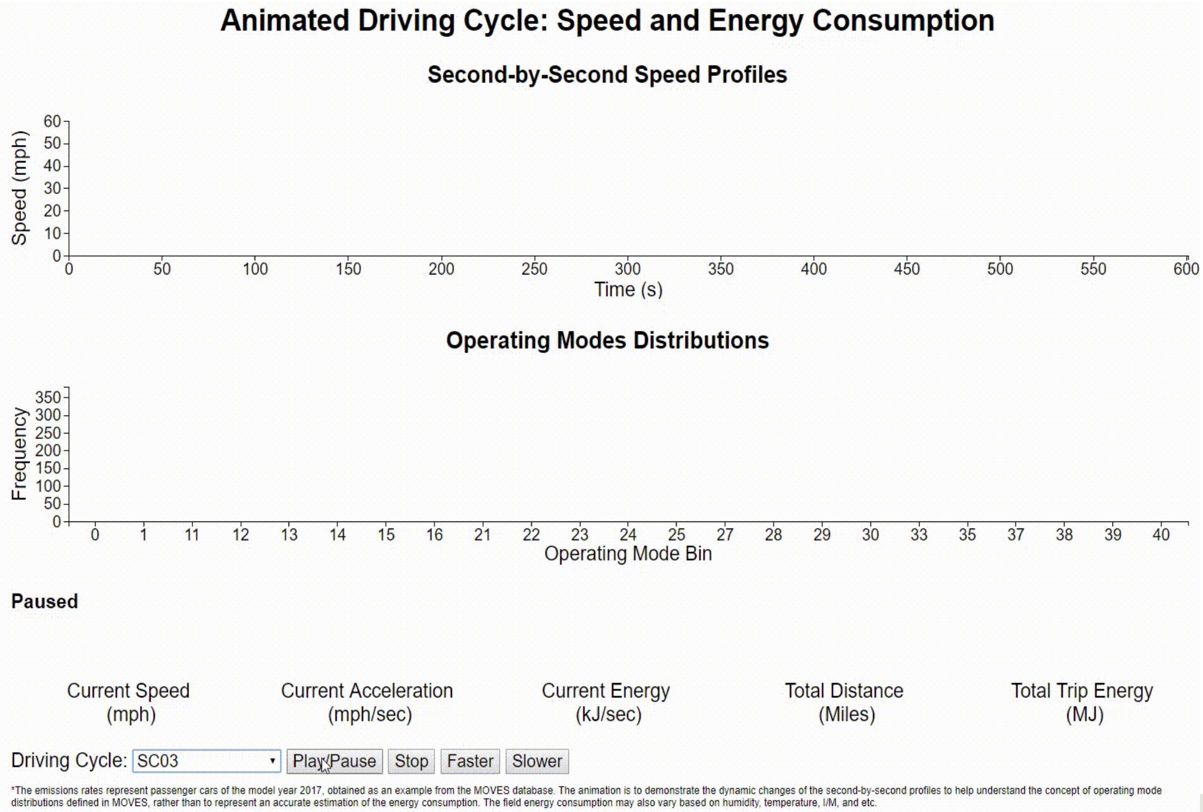
IM240 Driving Cycle



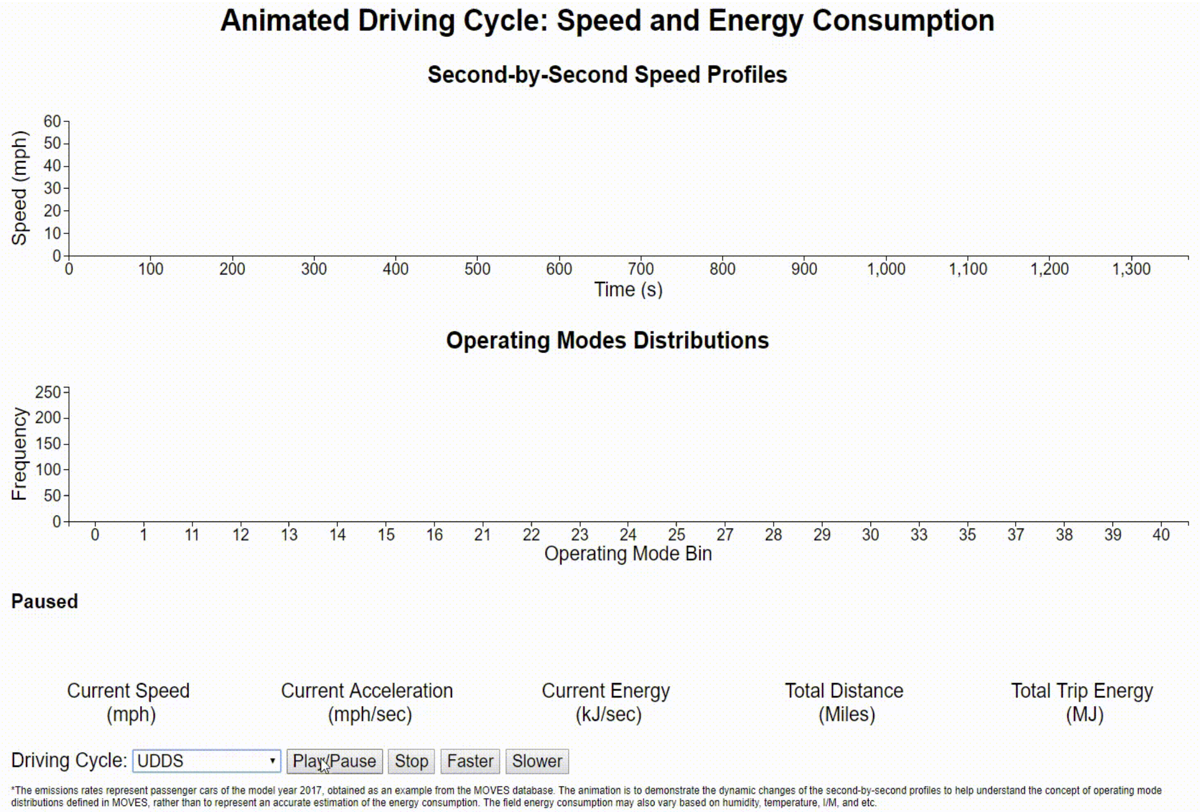
NYCC Driving Cycle



SC03 Driving Cycle



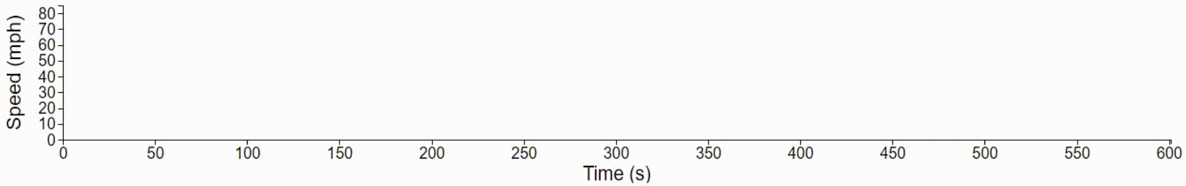
UDDS Driving Cycle



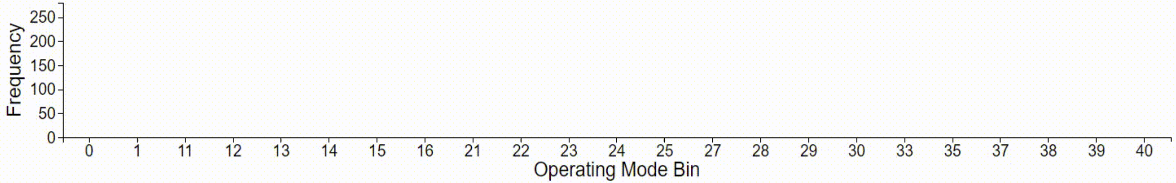
US06 Driving Cycle

Animated Driving Cycle: Speed and Energy Consumption

Second-by-Second Speed Profiles



Operating Modes Distributions



Paused

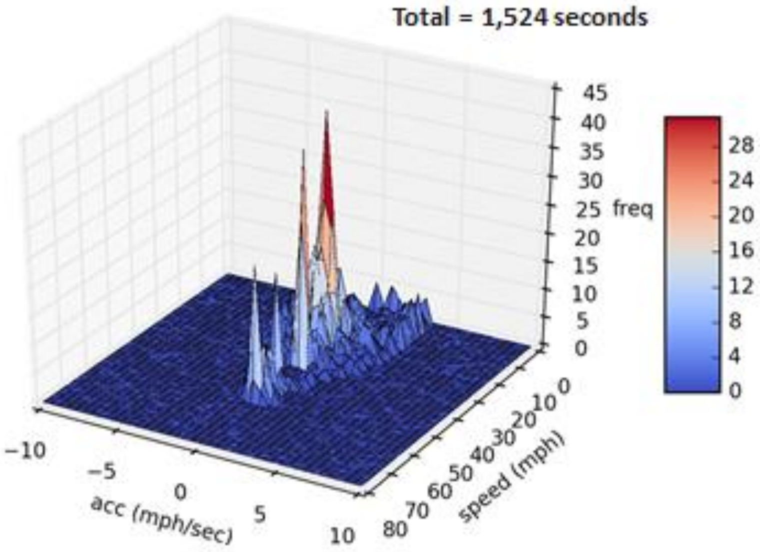
Current Speed (mph)	Current Acceleration (mph/sec)	Current Energy (kJ/sec)	Total Distance (Miles)	Total Trip Energy (MJ)

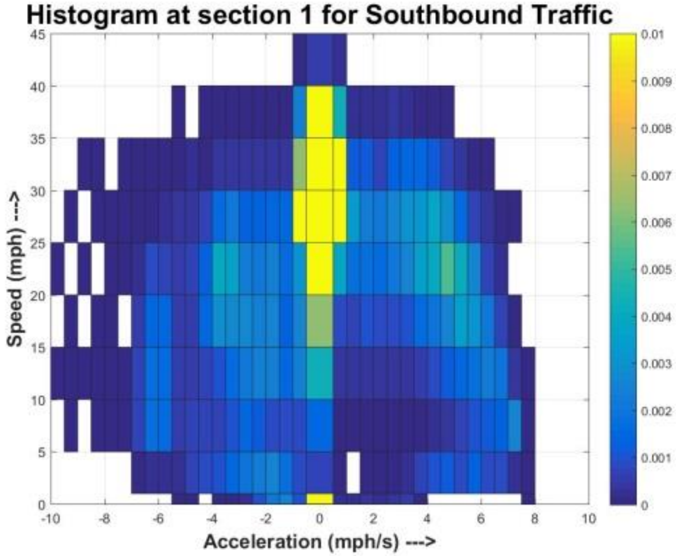
Driving Cycle: US06 | Play/Pause | Stop | Faster | Slower

*The emissions rates represent passenger cars of the model year 2017, obtained as an example from the MOVES database. The animation is to demonstrate the dynamic changes of the second-by-second profiles to help understand the concept of operating mode distributions defined in MOVES, rather than to represent an accurate estimation of the energy consumption. The field energy consumption may also vary based on humidity, temperature, I/M, and etc.

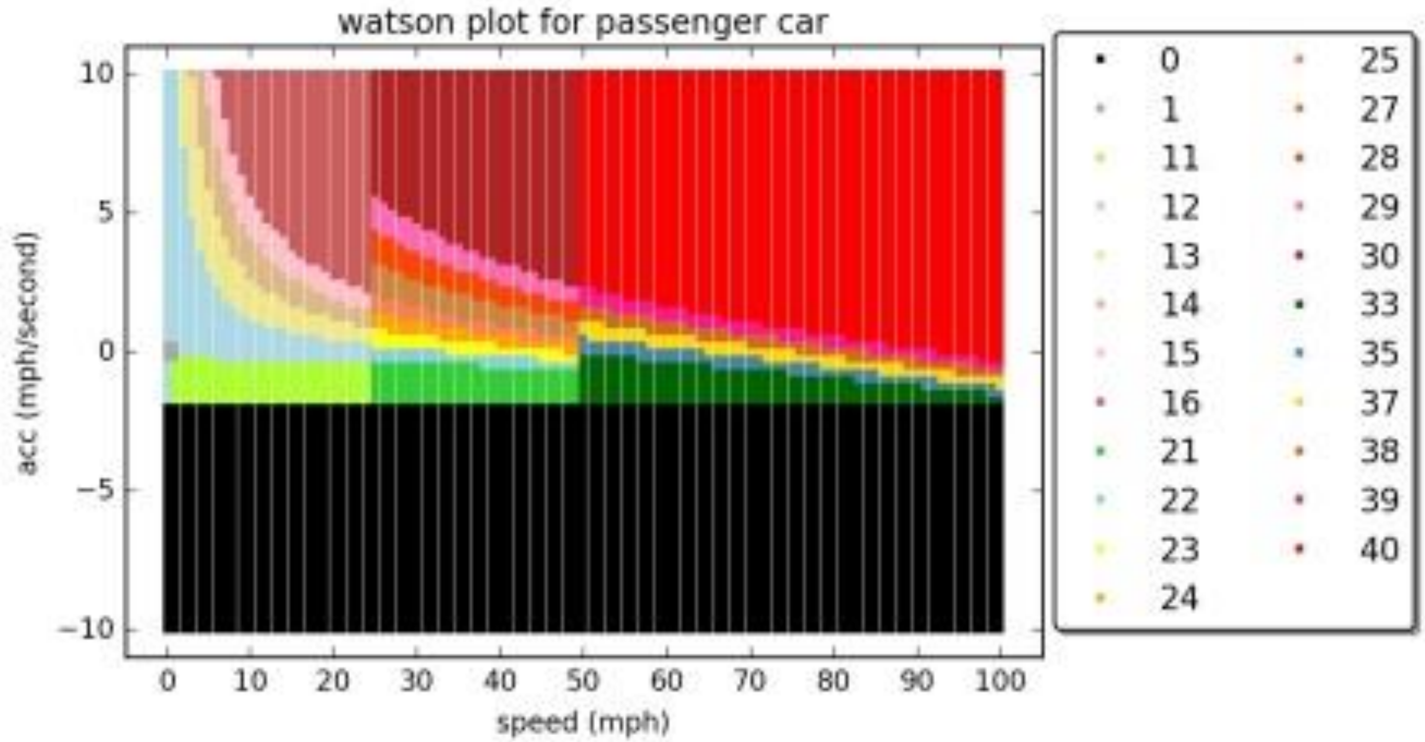
MOVES Energy/Emission Rates Mapped to Speed/Acceleration Distributions

Watson Plots of Vehicle Activity: Speed/Acceleration Frequency Distributions

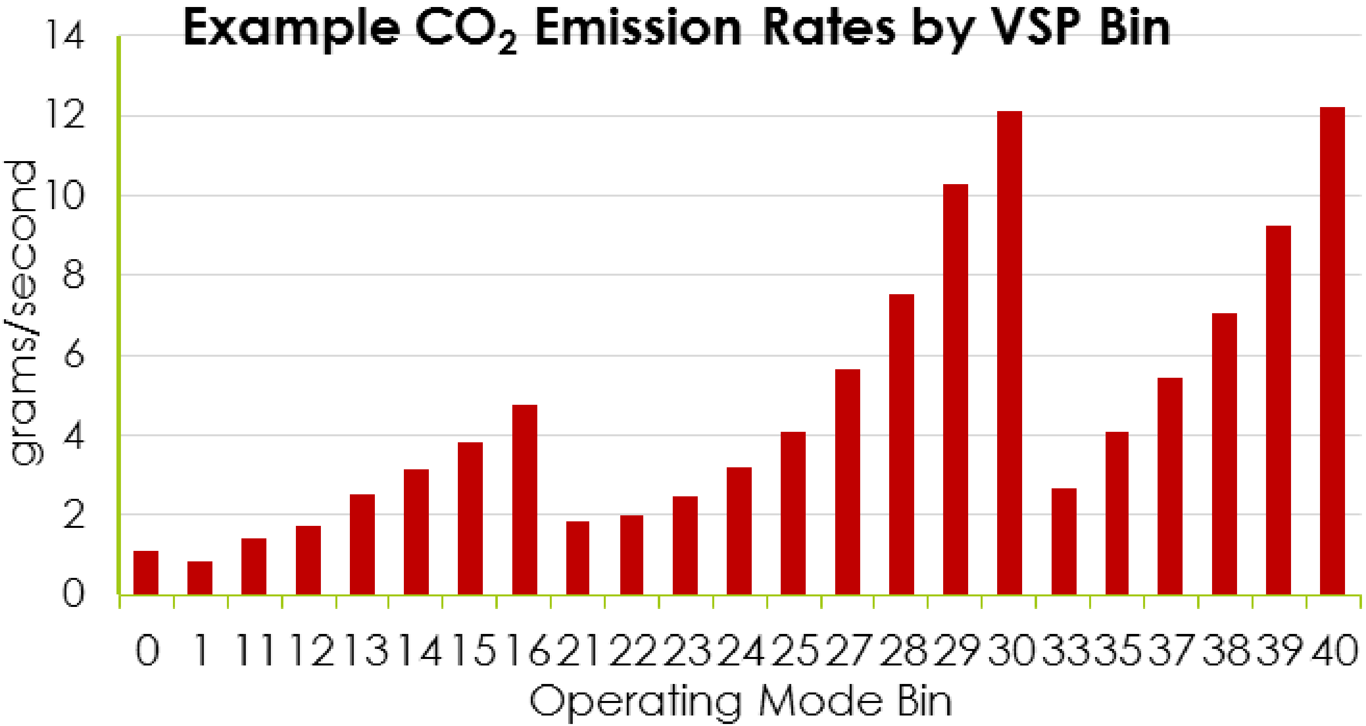




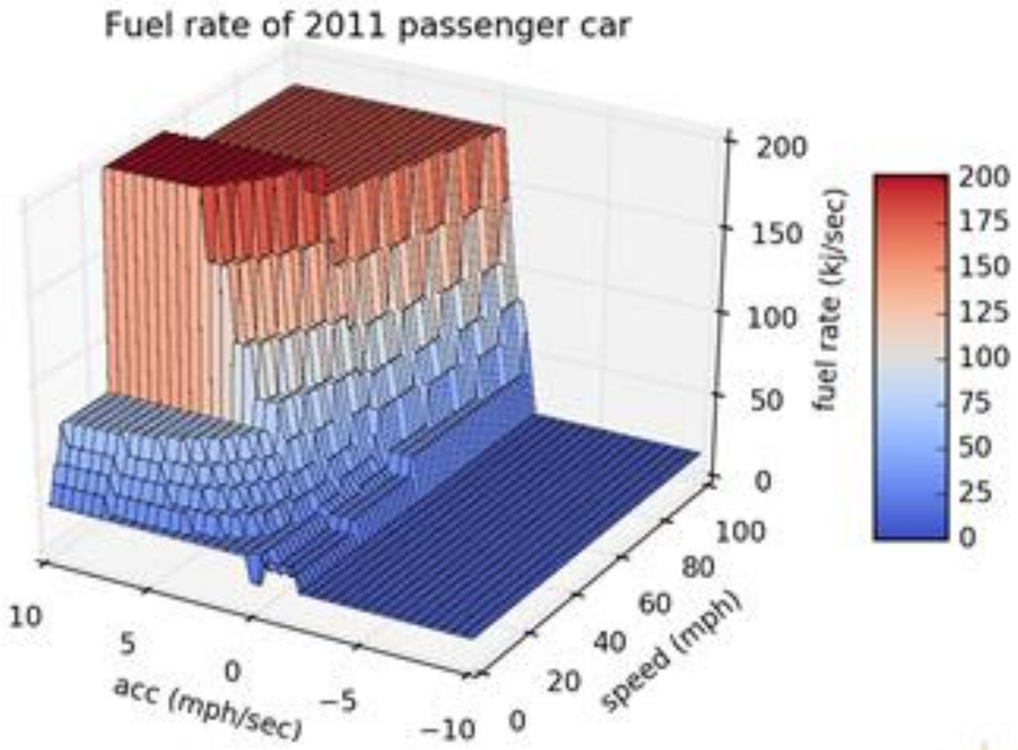
Watson Plot Activity Mapped to VSP Bins: Passenger Car Example



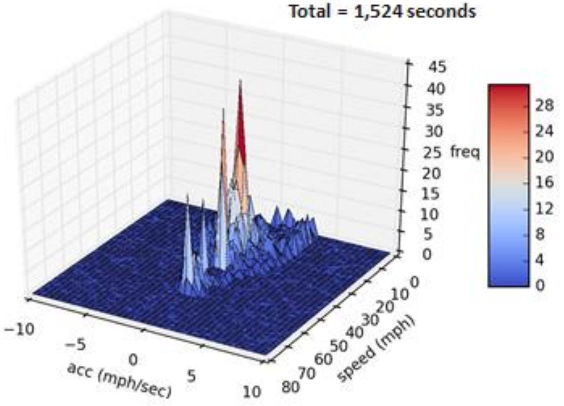
Assign MOVES Energy/Emission Rates to Watson Plot Cells



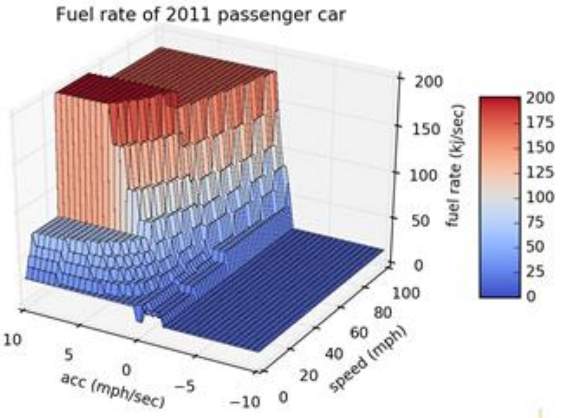
Energy/Emissions Rate Map by Watson Bin 2011 MY Passenger Car



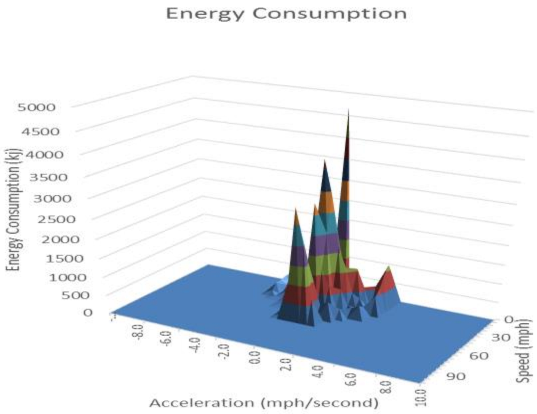
Calculate Energy/Emissions From Watson Plot and MOVES Rate Map



FTP Driving Cycle
(Idle not displayed)



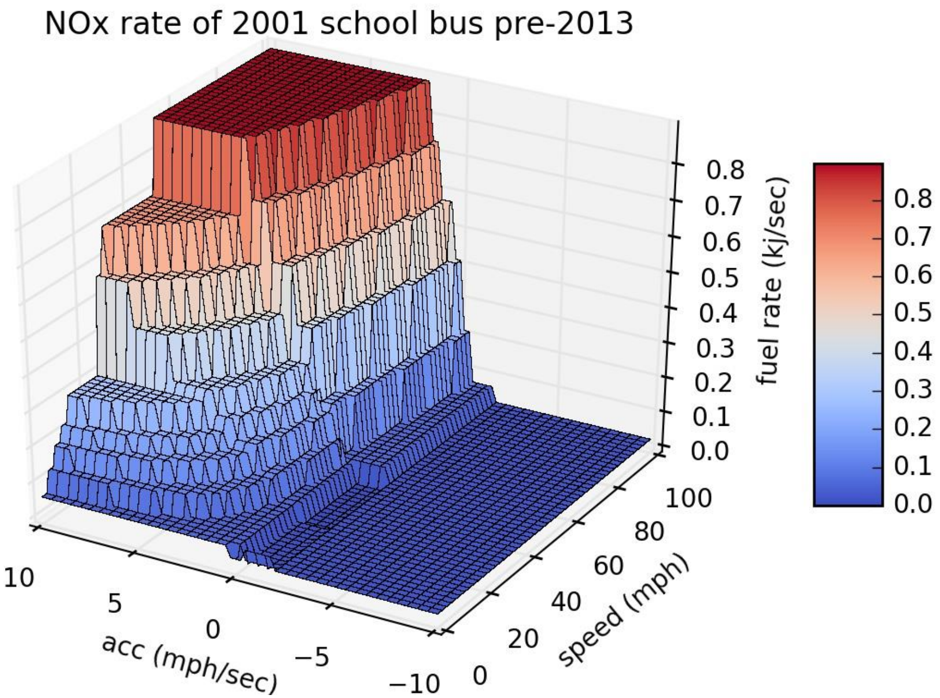
FTP Fuel Rates
2011 MY Passenger Car



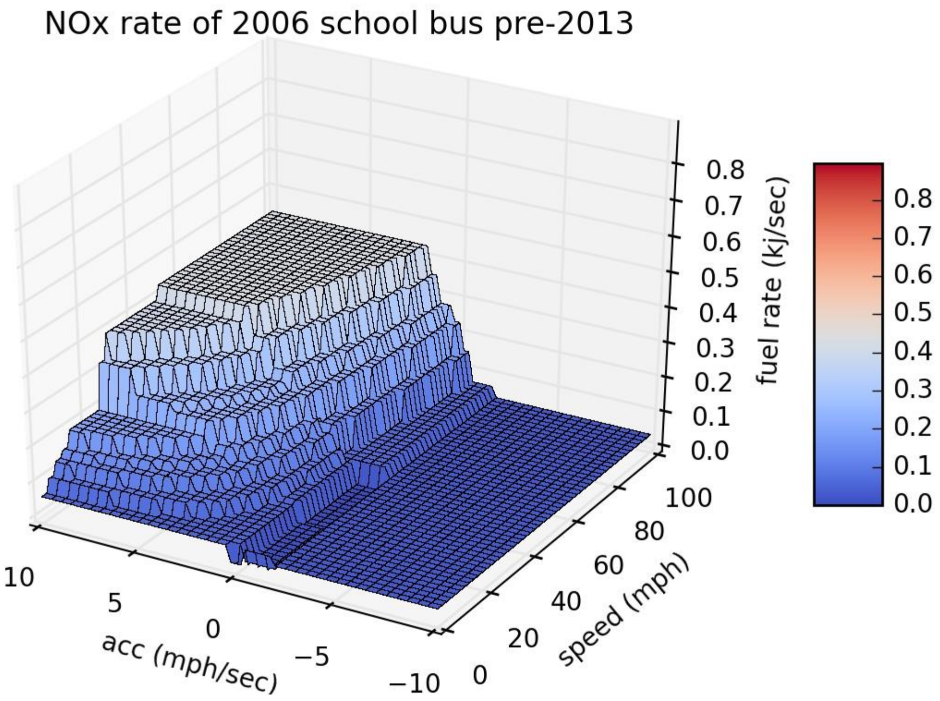
FTP Energy Use by Bin
2011 MY Passenger Car

School Bus
NOx Emission Rates

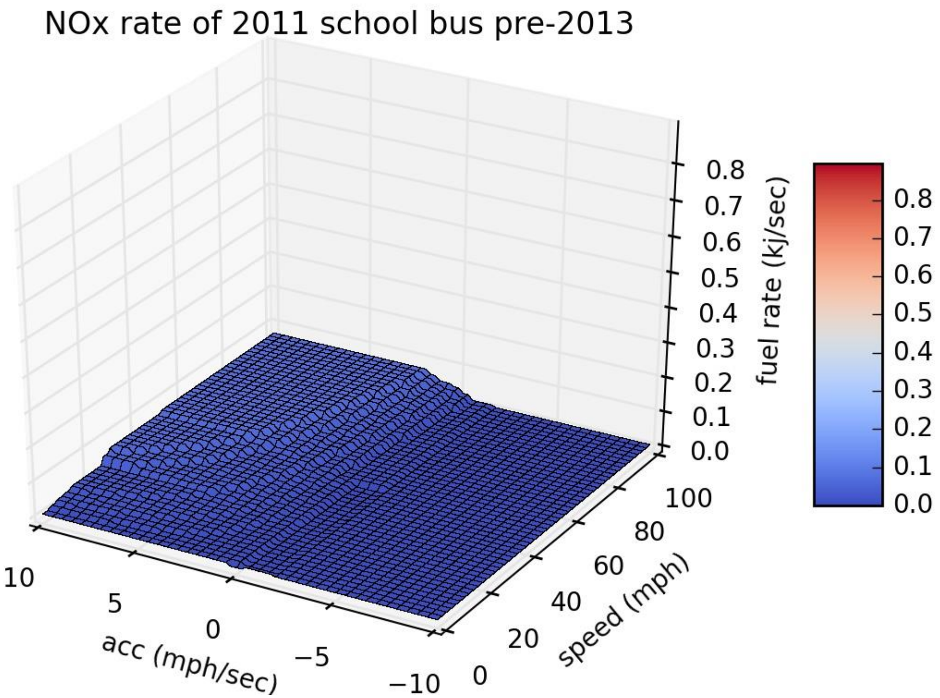
School Bus MY2001
NOx Emission Rates



School Bus MY2006
NOx Emission Rates



School Bus MY2011 NOx Emission Rates



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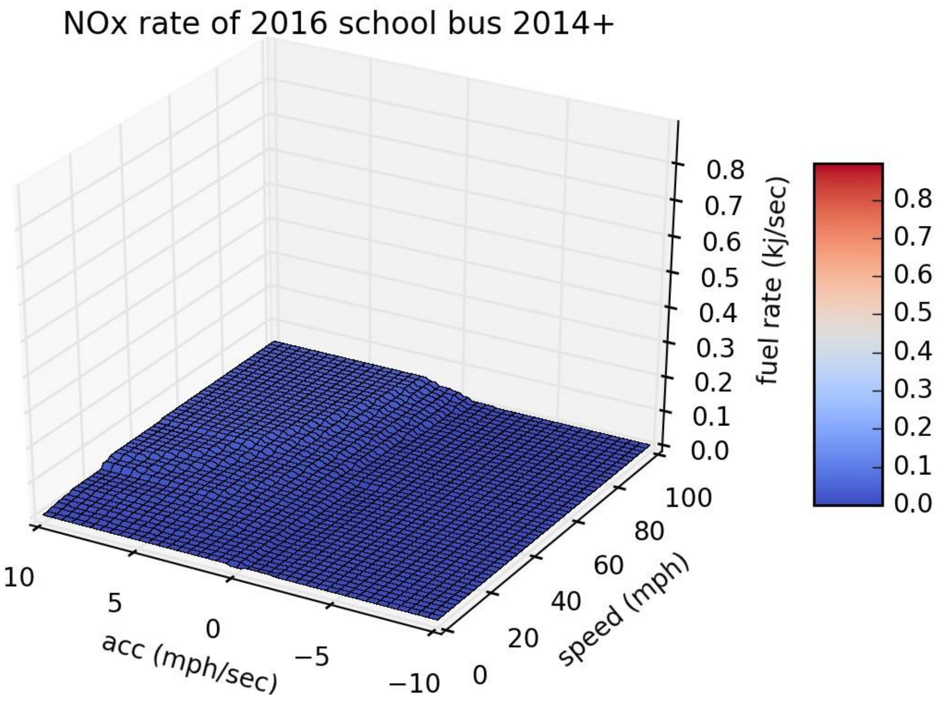
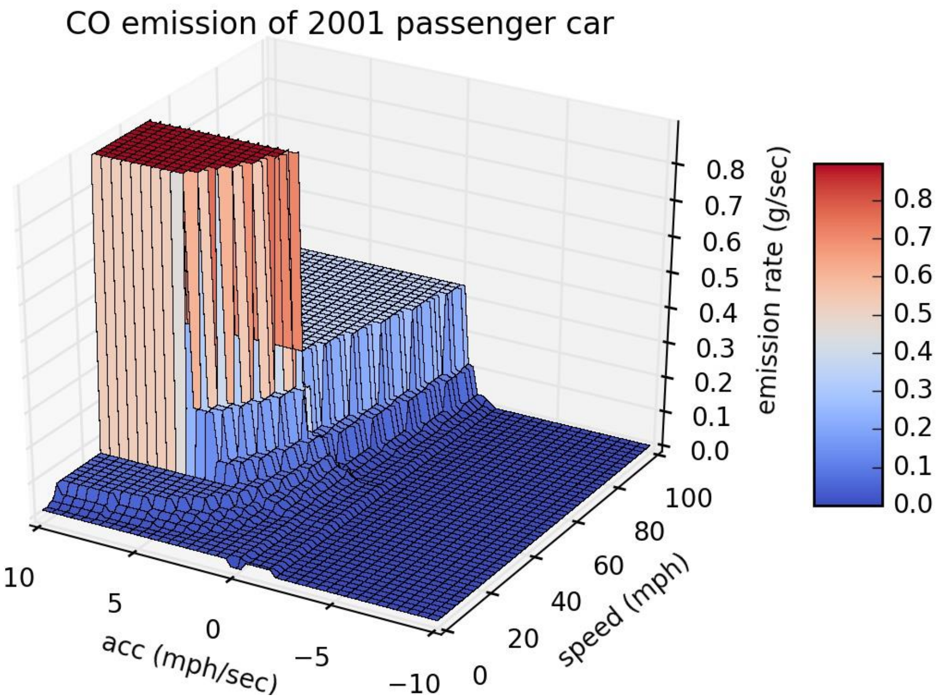
School Bus MY2016 NOx Emission Rates

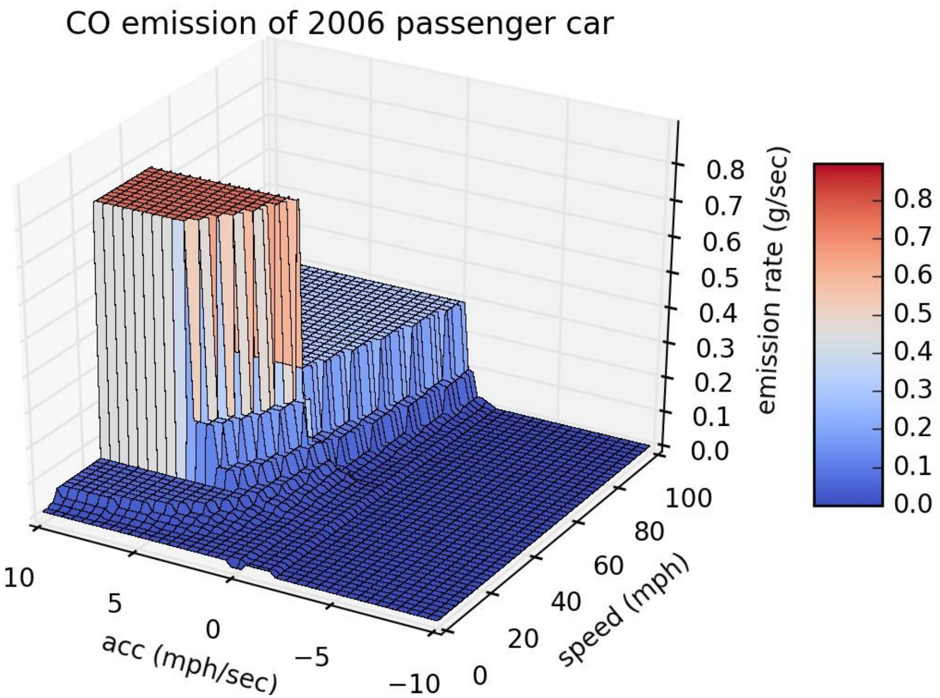


Passenger Car
CO Emission Rates

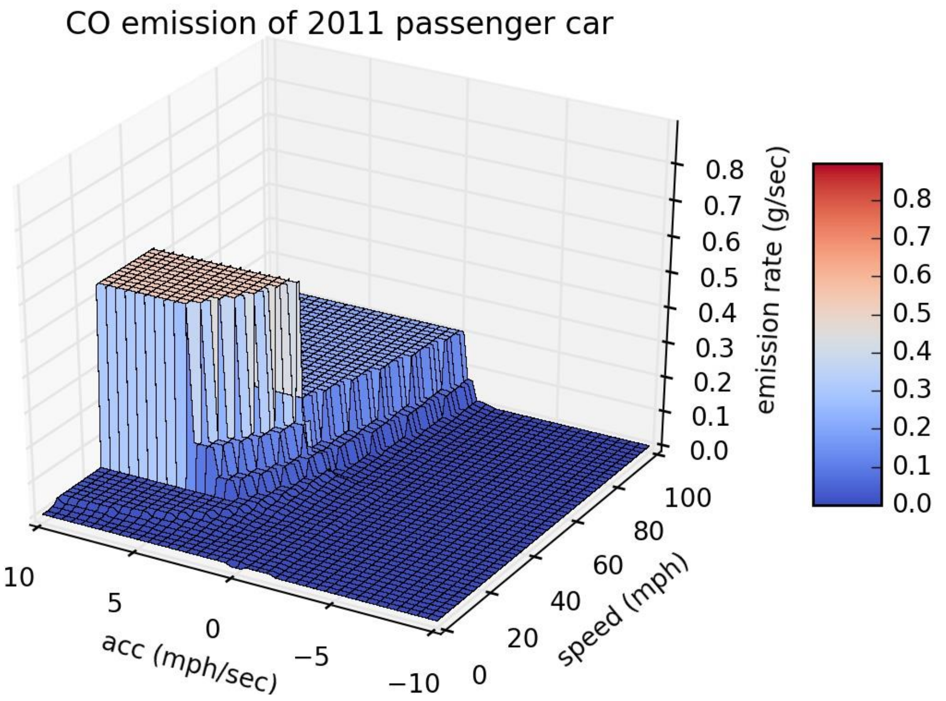
Passenger Car MY2001 CO Emission Rates



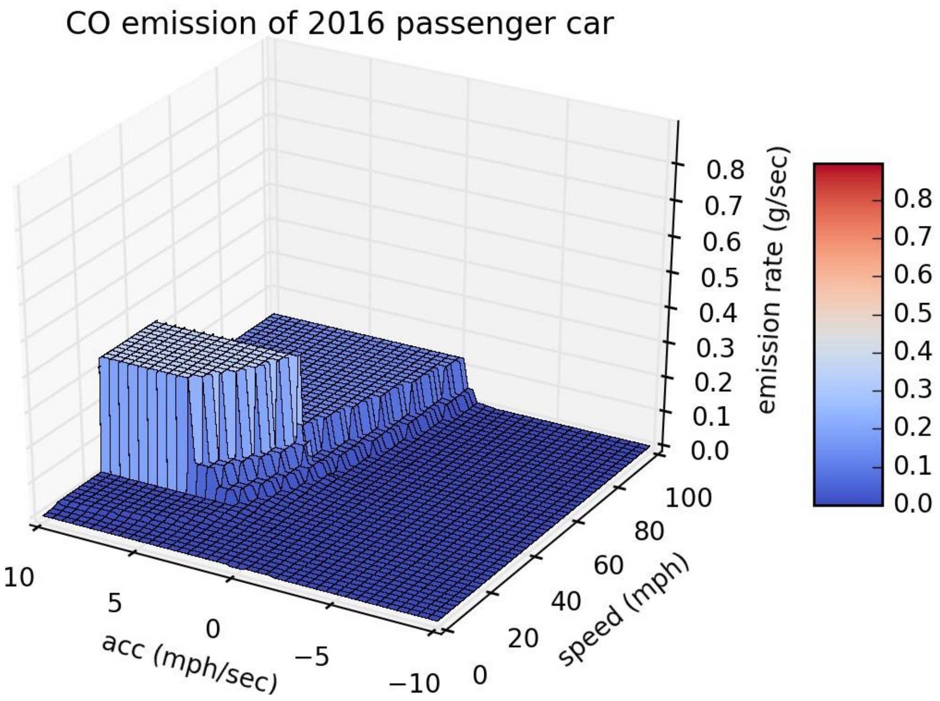
Passenger Car MY2006
CO Emission Rates



Passenger Car MY2011
CO Emission Rates

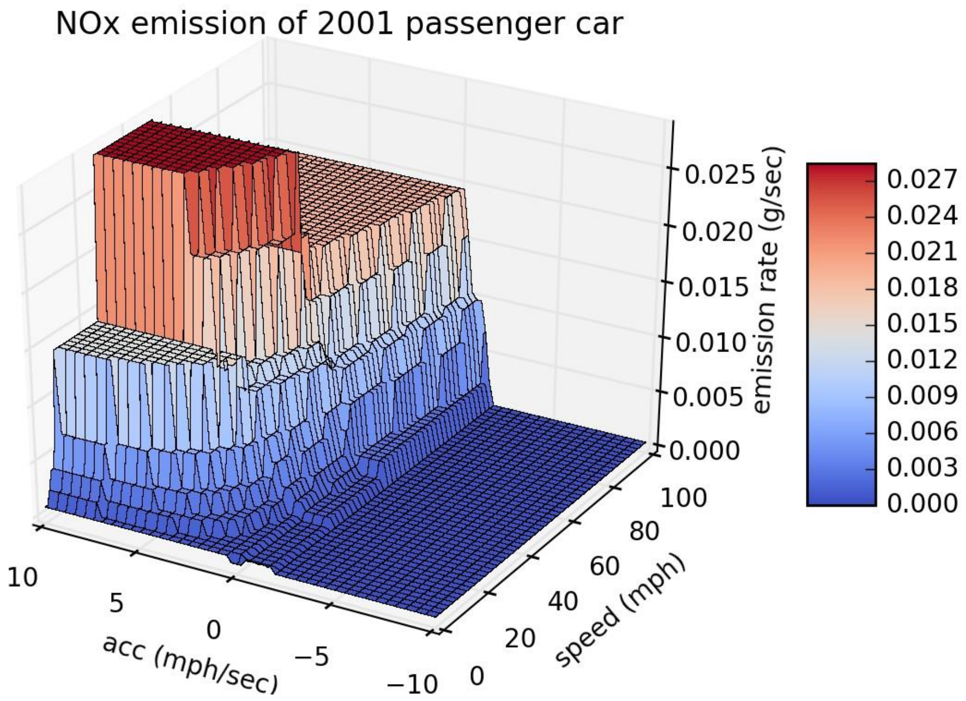


Passenger Car MY2016 CO Emission Rates

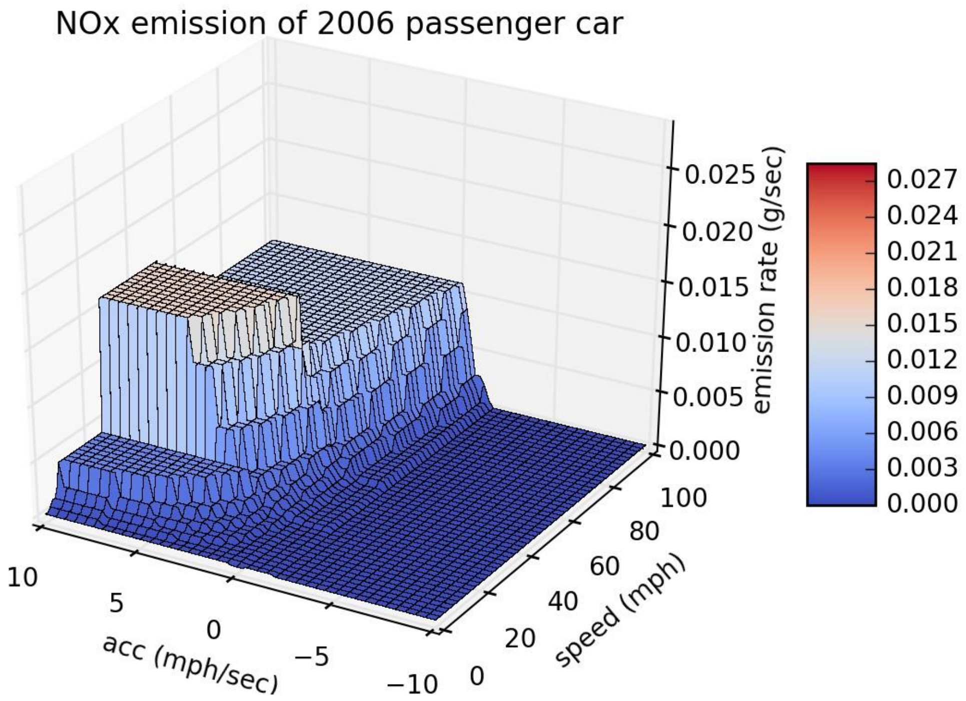


Passenger Car
NOx Emission Rates

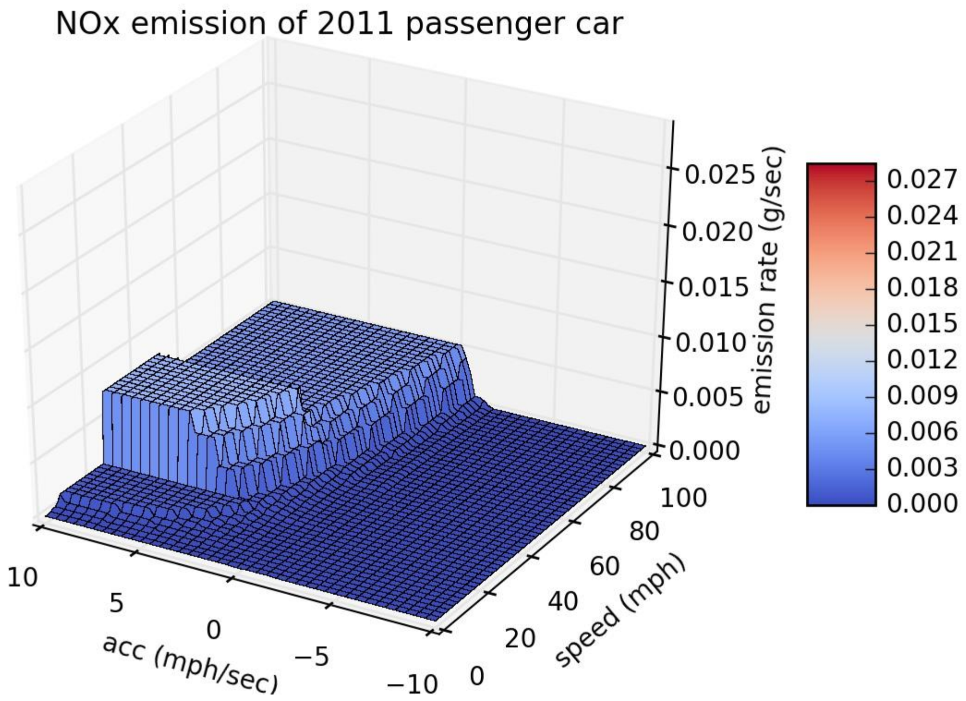
Passenger Car MY2001 NOx Emission Rates



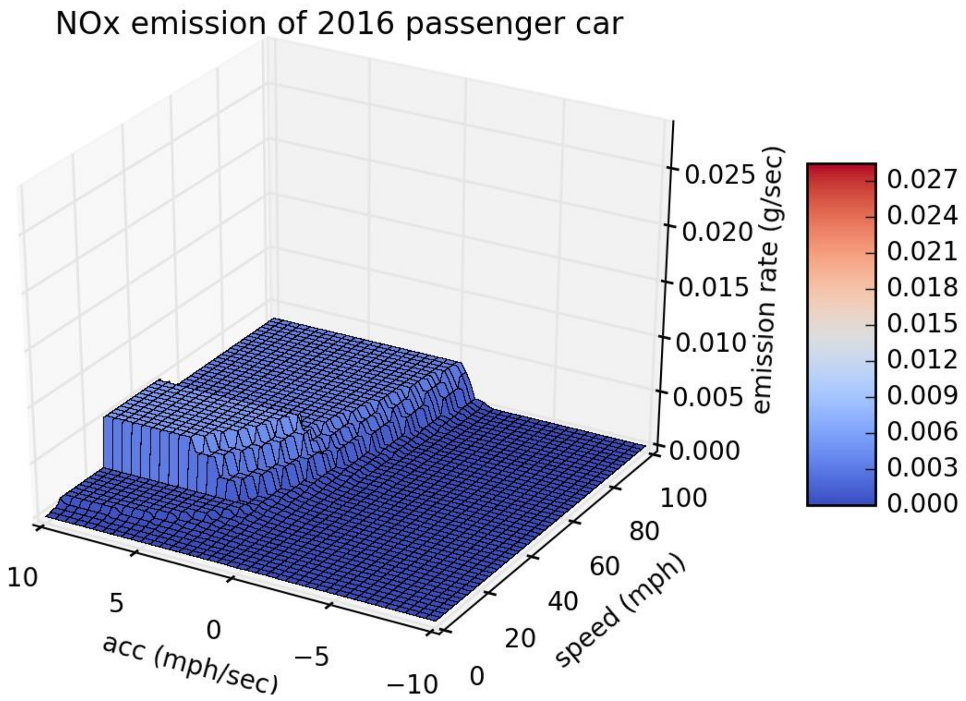
Passenger Car MY2006
NOx Emission Rates



Passenger Car MY2011
NOx Emission Rates

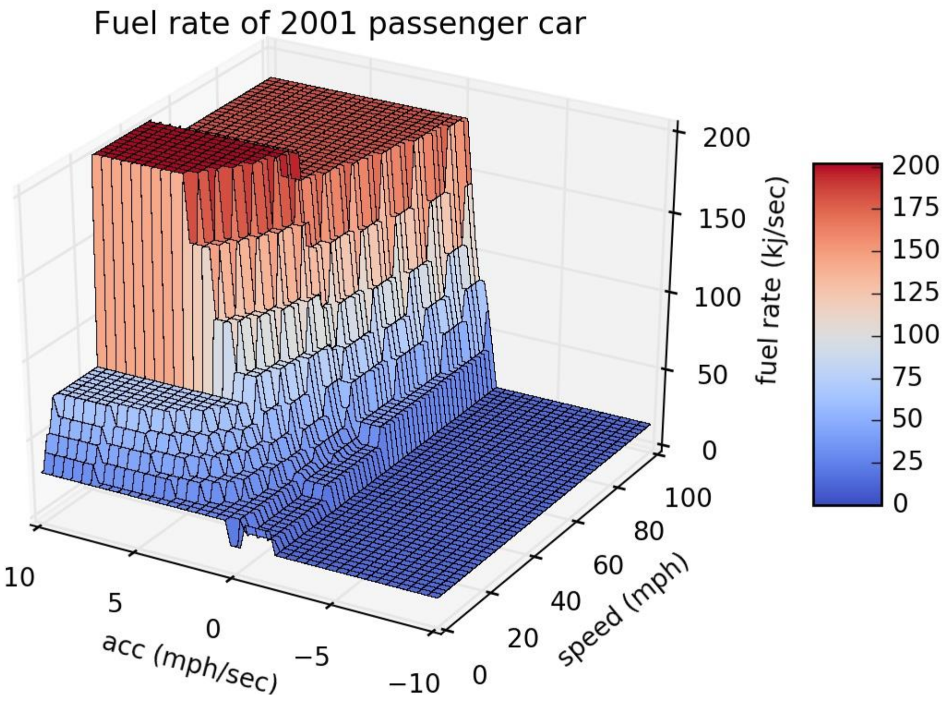


Passenger Car MY2016
NOx Emission Rates

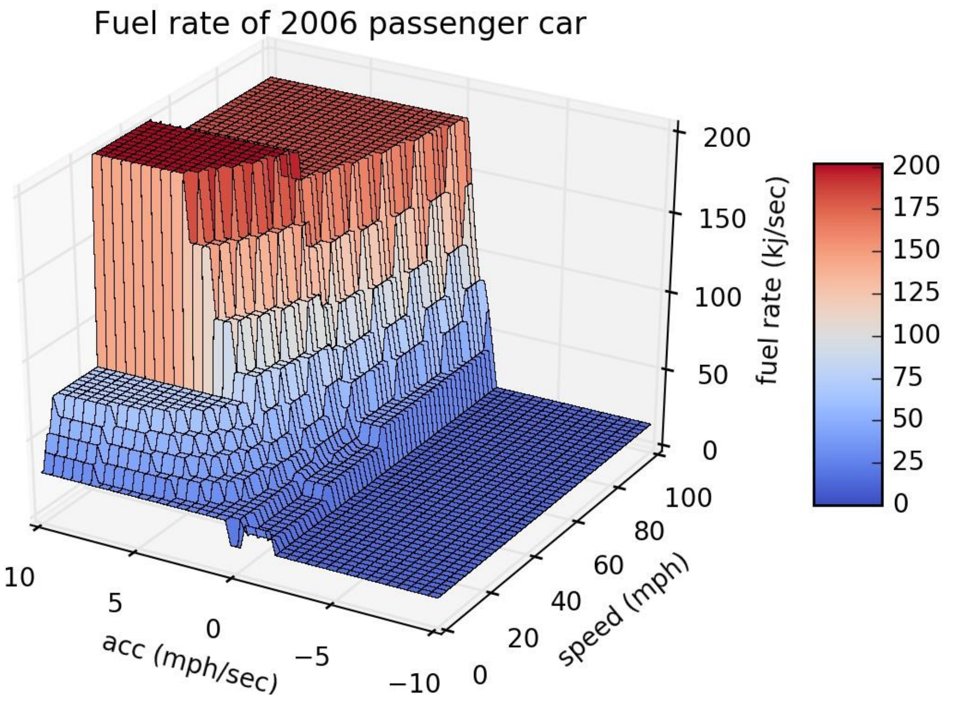


Passenger Car
Fuel Consumption Rates

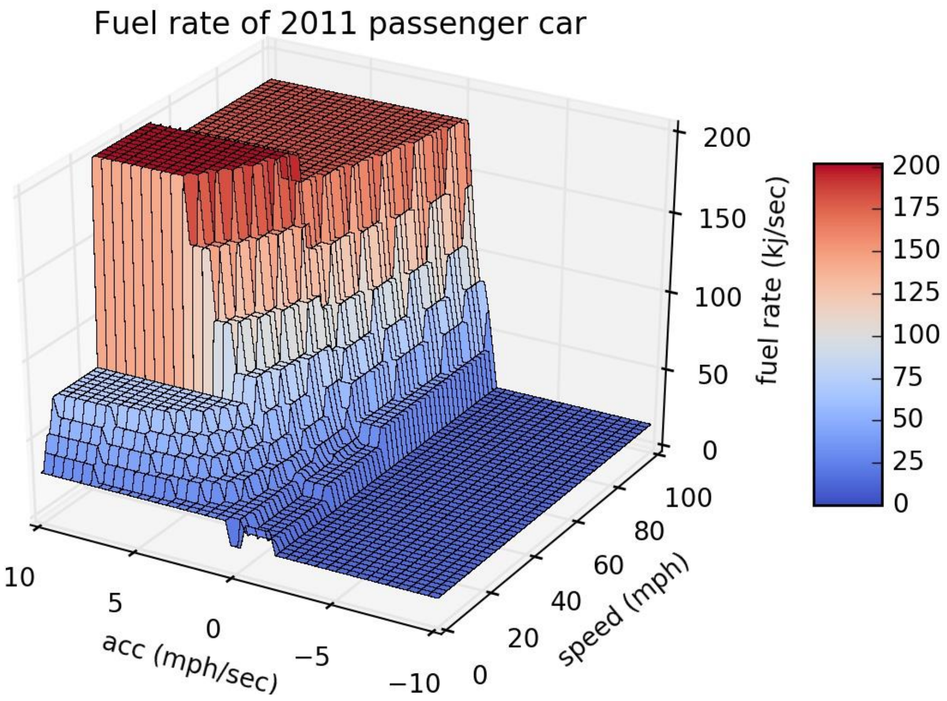
Passenger Car MY2001
Fuel Rates



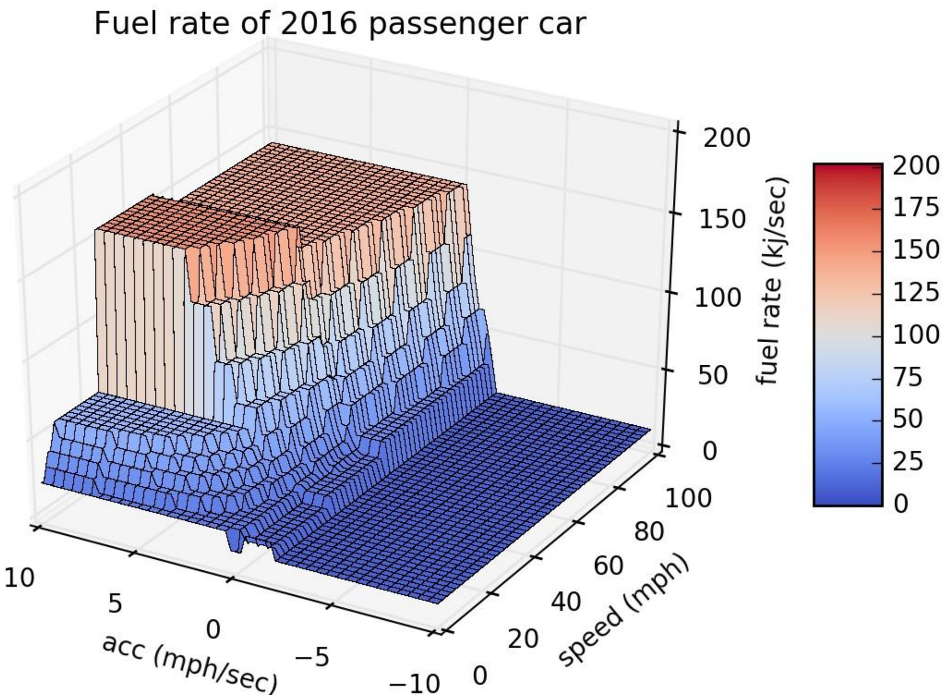
Passenger Car MY2006 Fuel Rates



Passenger Car MY2011
Fuel Rates



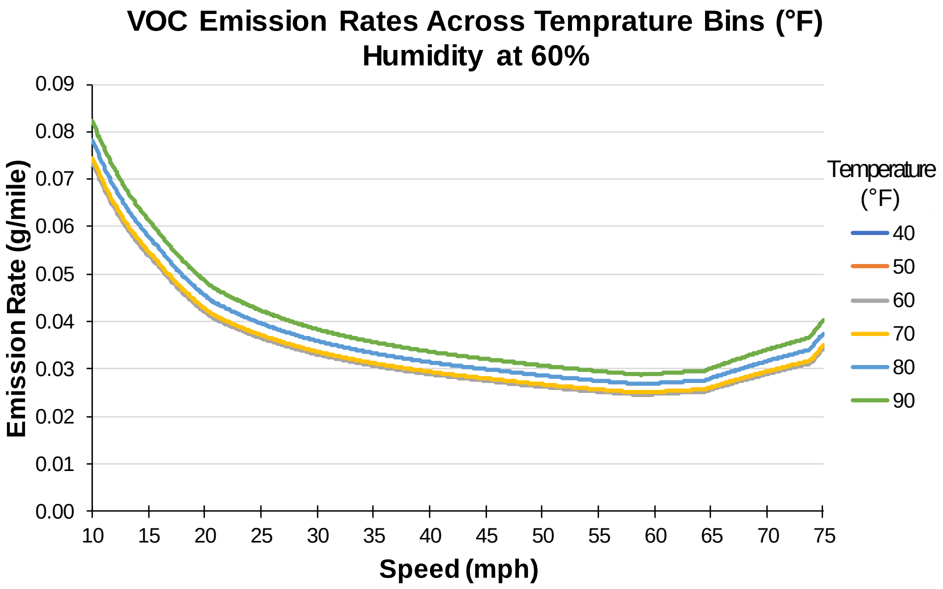
Passenger Car MY2016
Fuel Rates

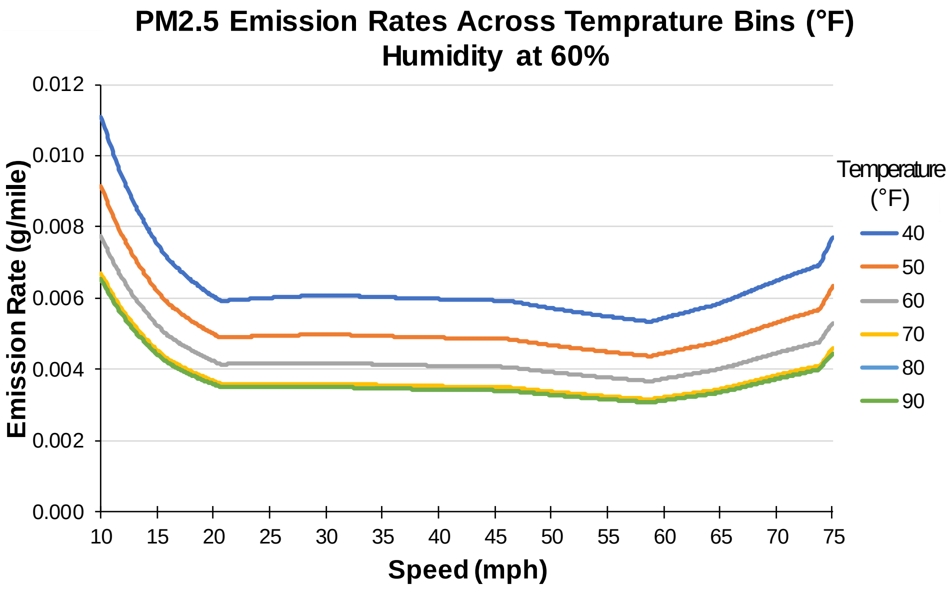


Other Parameters that Influence MOVES Energy/Emission Rates

- Braking
- Road grade
- Fuel specifications (e.g., summer/winter/transition fuels)
- Inspection and maintenance (I/M) programs
  - Reduces fraction of high-emitting vehicles in the fleet
- Environmental conditions
  - Temperature
  - Humidity

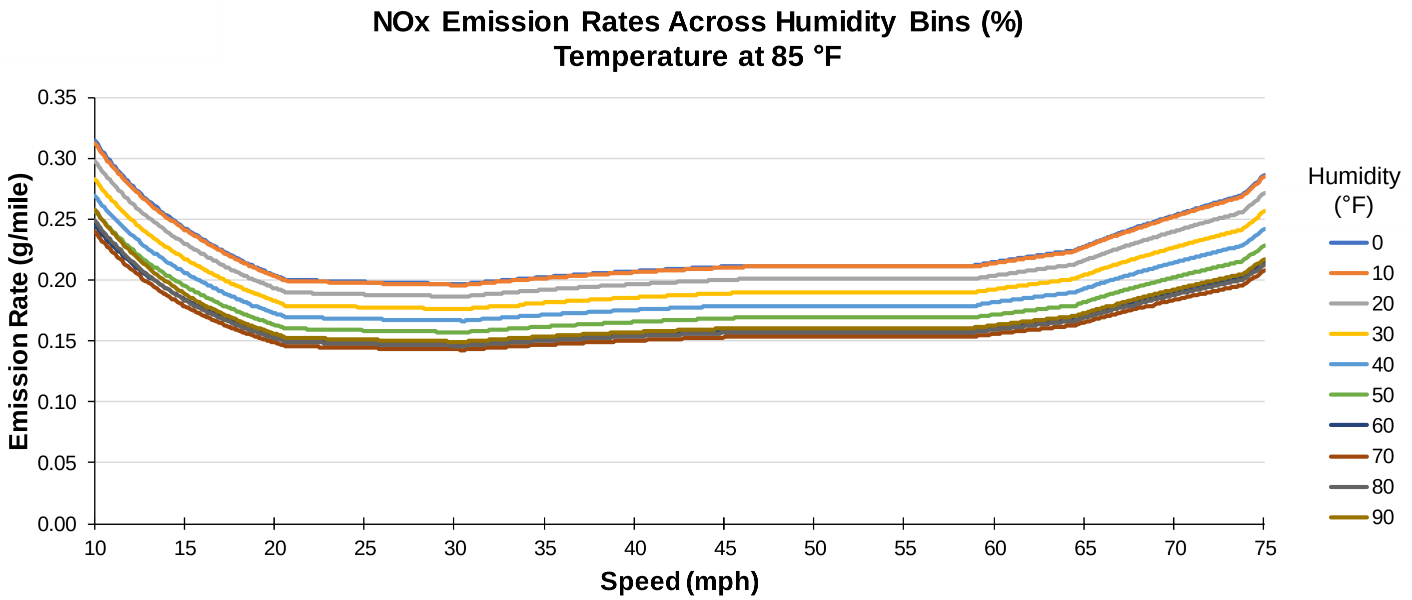
MOVES Sensitivity of Meteorology Temperature





* Source type of 21 (Passenger Car), national default age distributions by EPA, Fulton County, GA April 2018, urban restricted highway, road grade of zero

MOVES Sensitivity of Meteorology Humidity



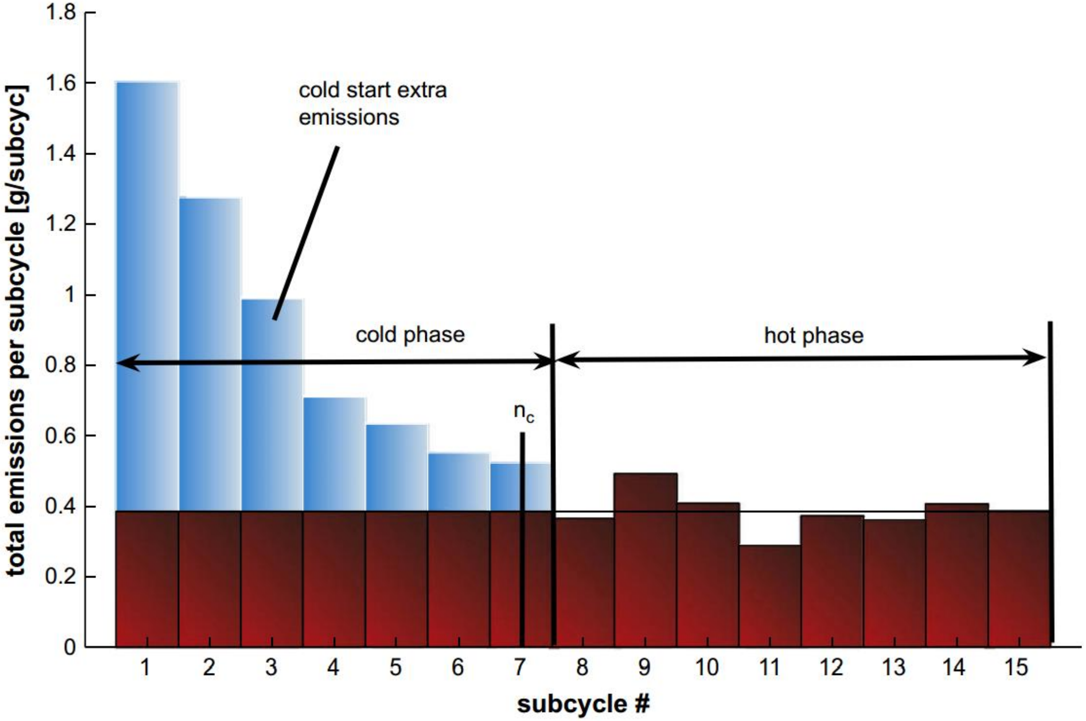
* Source type of 21 (Passenger Car), national default age distributions by EPA, Fulton County, GA April 2018, urban restricted highway, road grade of zero

MOVES Modeling for Engine Start Emissions

Start Emissions

- A cold engine block and low coolant temperatures results in incomplete combustion and significantly higher emissions during combustion stabilization
- Starts are an important source of HC, CO, NOx, and PM
- Start emissions are represented as a function of temperature and soak time in MOVES
  - Soak time is the time between previous engine shut-off and next engine start (engine cool-down period)

Separation of Emissions into Cold and Hot Stabilized Phases



Source: Favez, et al., (2009) Cold start extra emissions as a function of engine stop time: Evolution over the last 10 years. Atmospheric Environment. 43., 996-1007

Modeling the Area Under the Start Curve
Start Modes are a Function of Soak Time

Soak OpMode ID	Description
101	Soak Time < 6 minutes
102	6 minutes <= Soak Time < 30 minutes
103	30 minutes <= Soak Time < 60 minutes
104	60 minutes <= Soak Time < 90 minutes
105	90 minutes <= Soak Time < 120 minutes
106	120 minutes <= Soak Time < 360 minutes
107	360 minutes <= Soak Time < 720 minutes
108	720 minutes <= Soak Time

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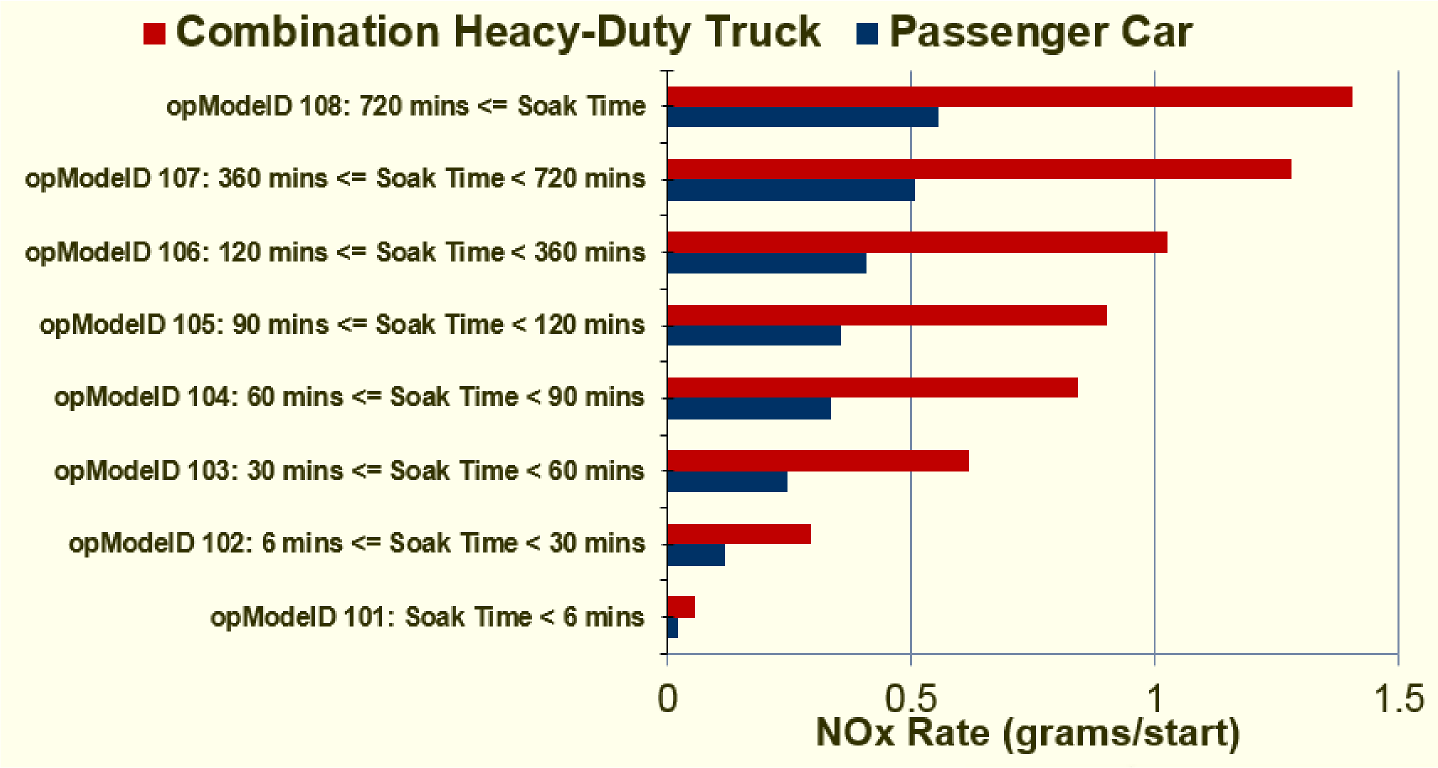
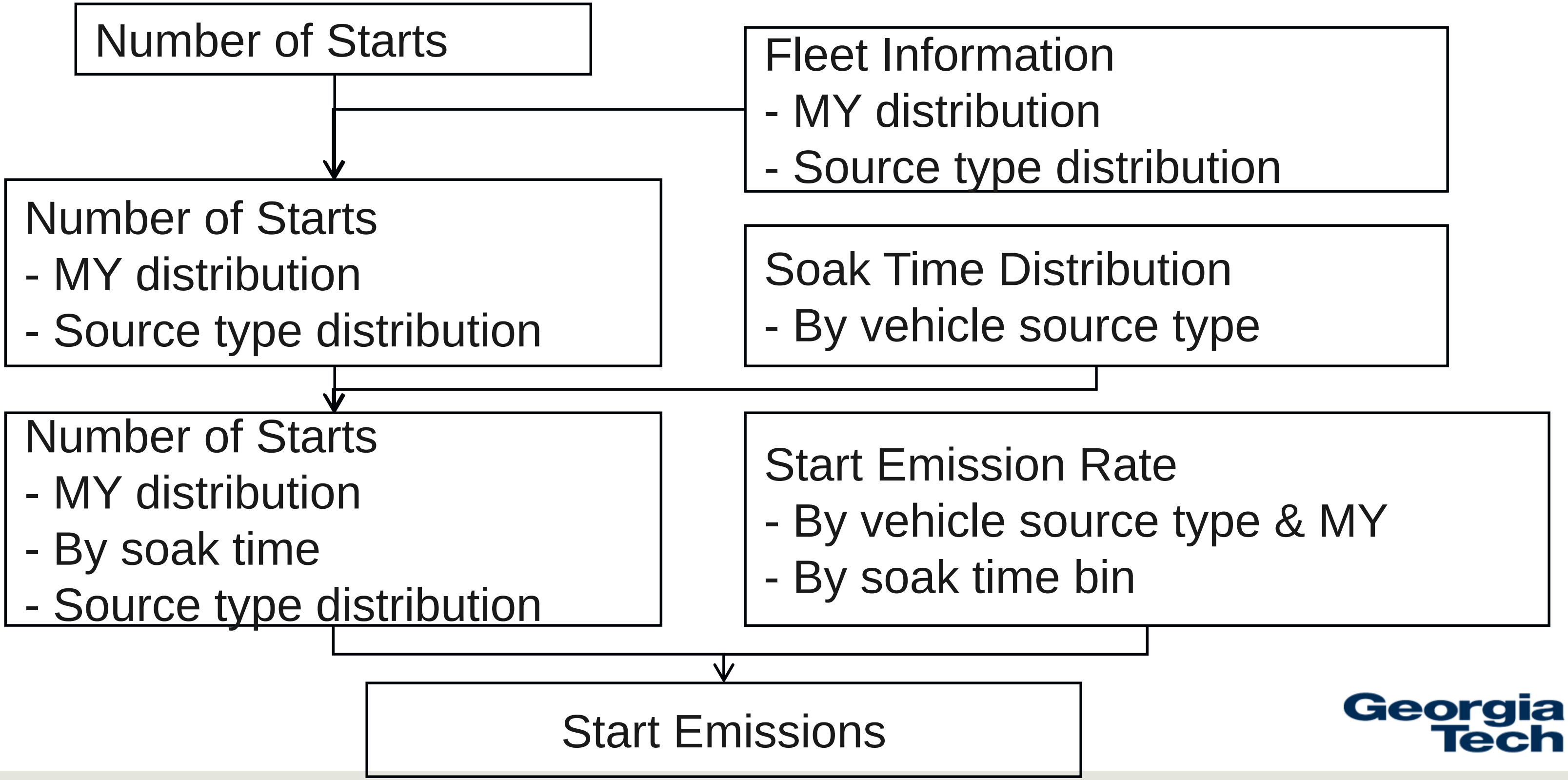
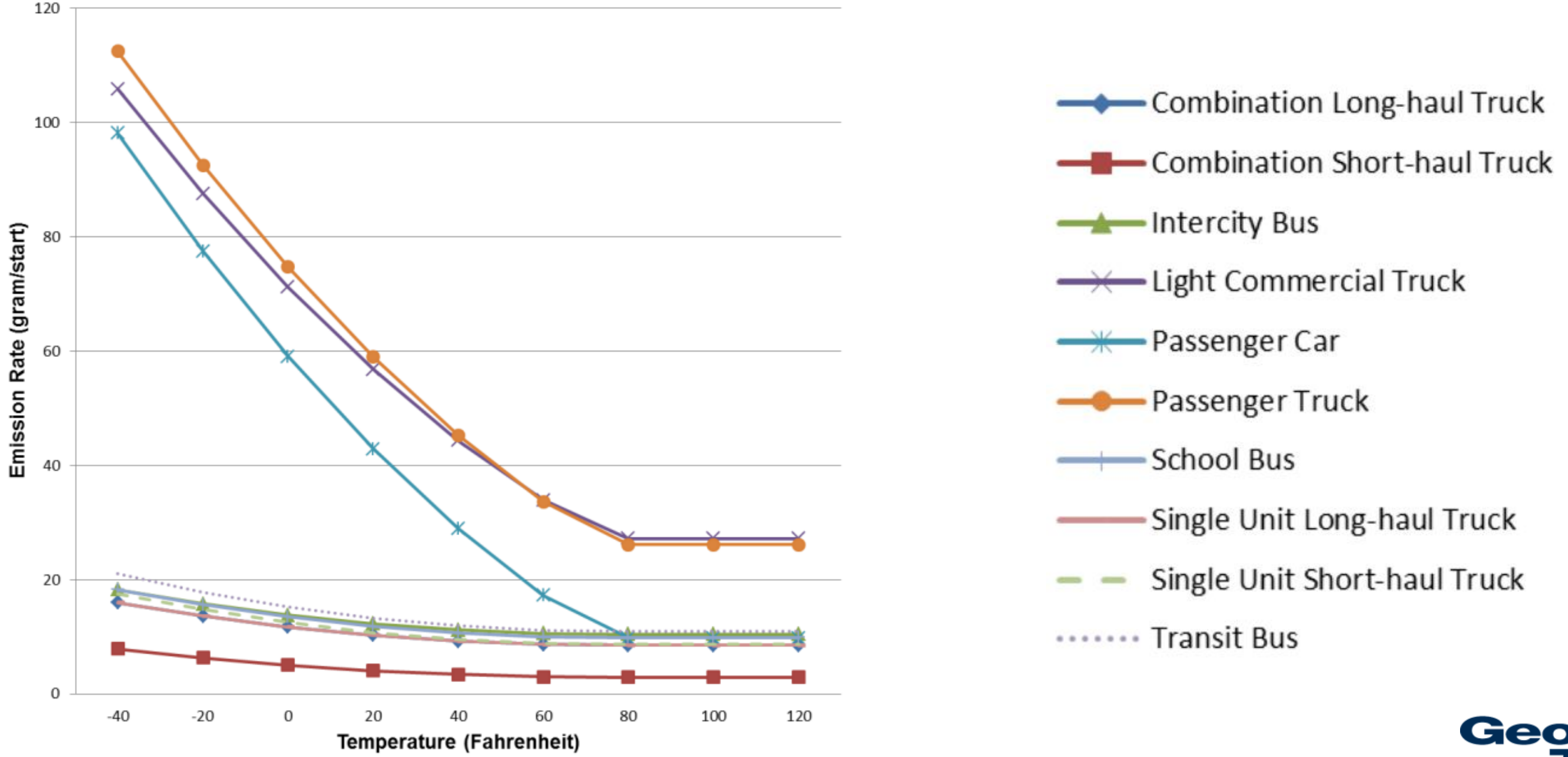
MOVES NOx Start Emission Rates for MY2010 Vehicles by Soak Time



Start Emission Modeling in MOVES



Start Emissions for CO Temperature Sensitivity



Noel, G and R. Wayson, (2012) MOVES2010a Regional Level Sensitivity Analysis. Volpe National Transportation System Center

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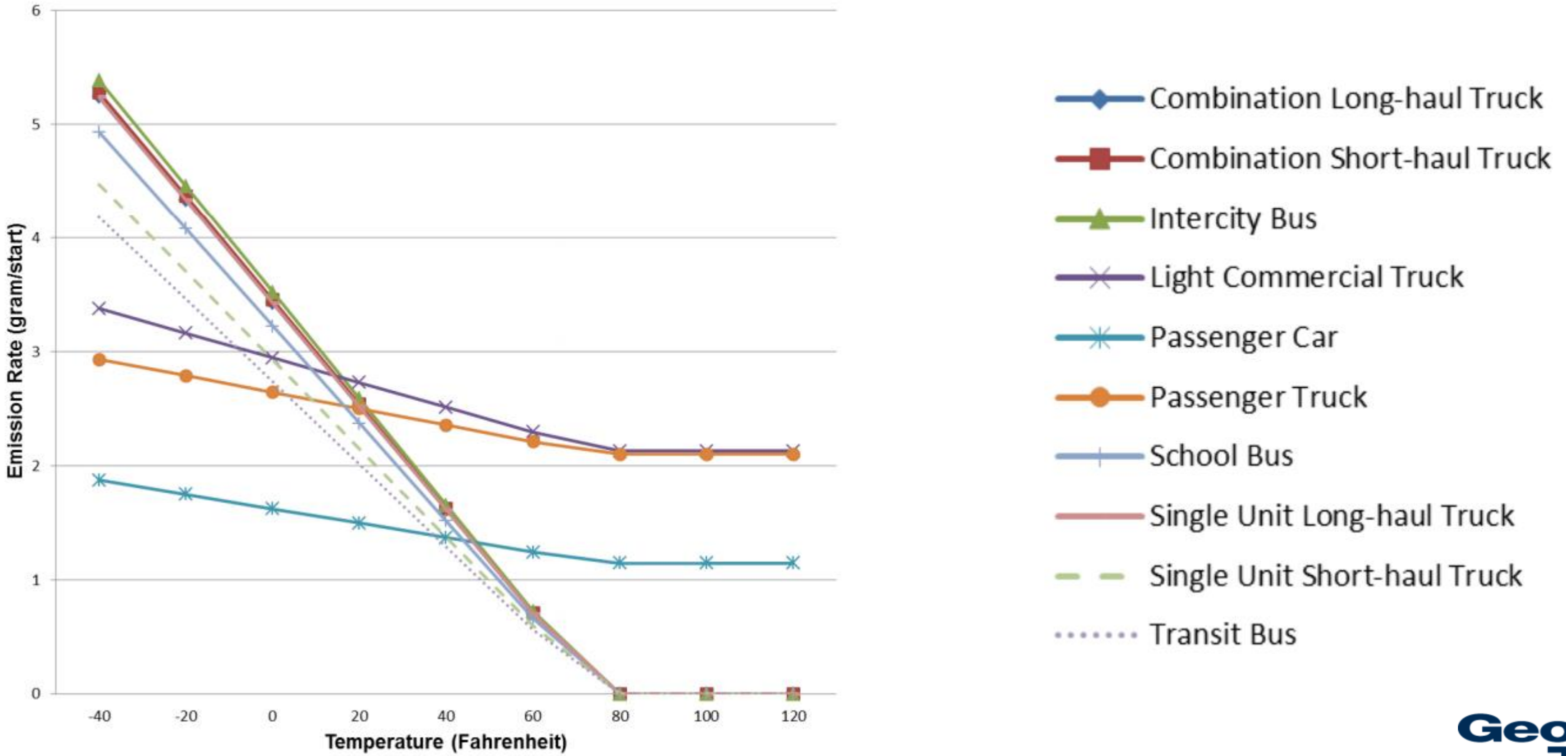
Start Emissions for NOx Temperature Sensitivity



Noel, G and R. Wayson, (2012) MOVES2010a Regional Level Sensitivity Analysis. Volpe National Transportation System Center

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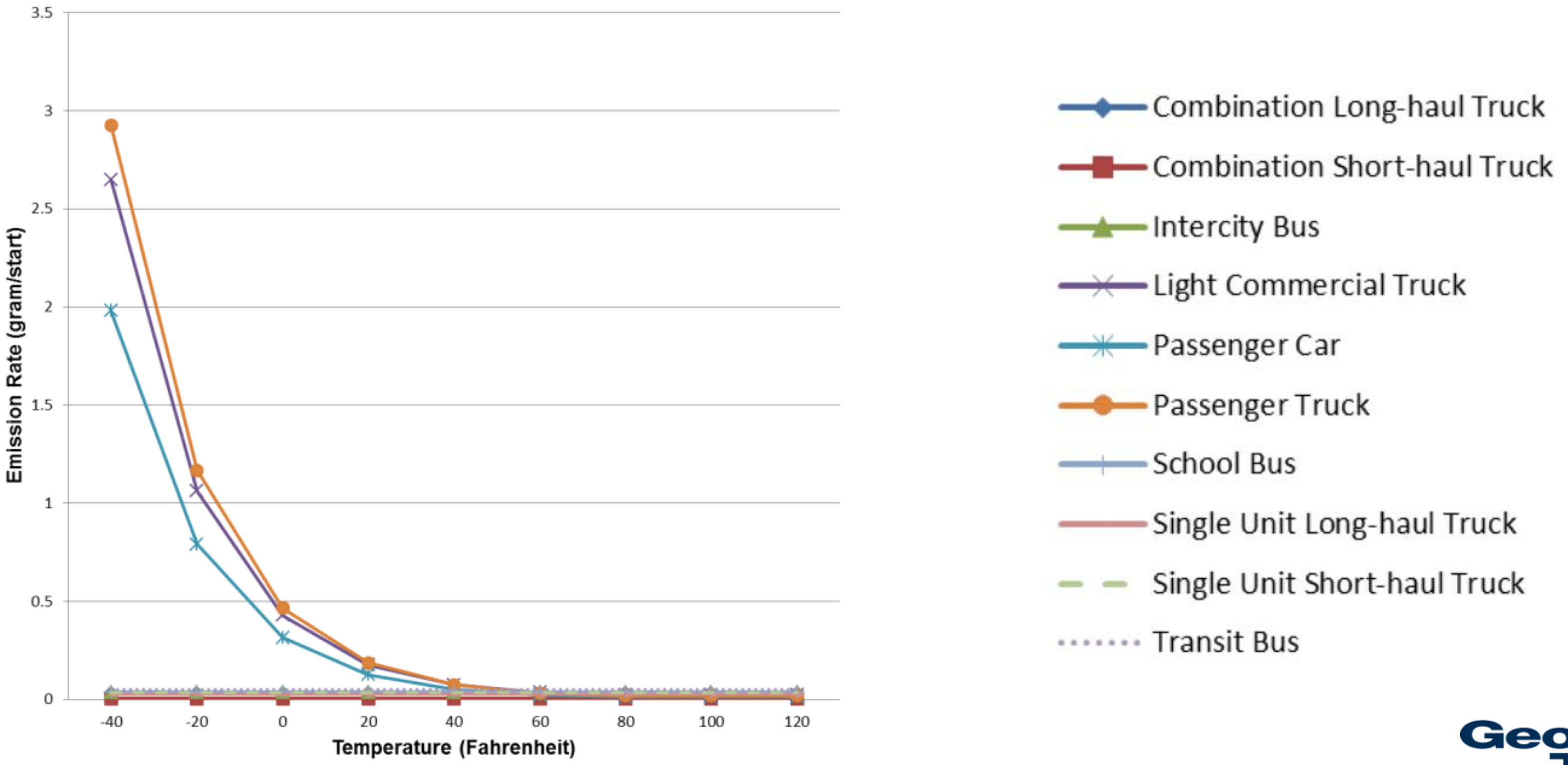
Starts Emissions for $PM_{2.5}$ Temperature Sensitivity

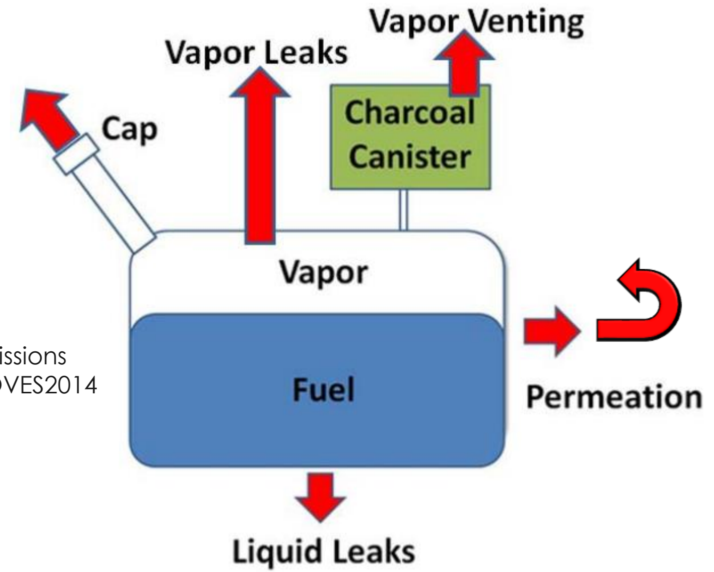


Noel, G and R. Wayson, (2012) MOVES2010a Regional Level Sensitivity Analysis. Volpe National Transportation System Center

MOVES Modeling for Evaporative Emissions

Evaporative Processes in MOVES

- Diurnal evaporation (fuel vapor)
- Liquid leaks
- Permeation (fuel to and from engine)
- Refueling emissions



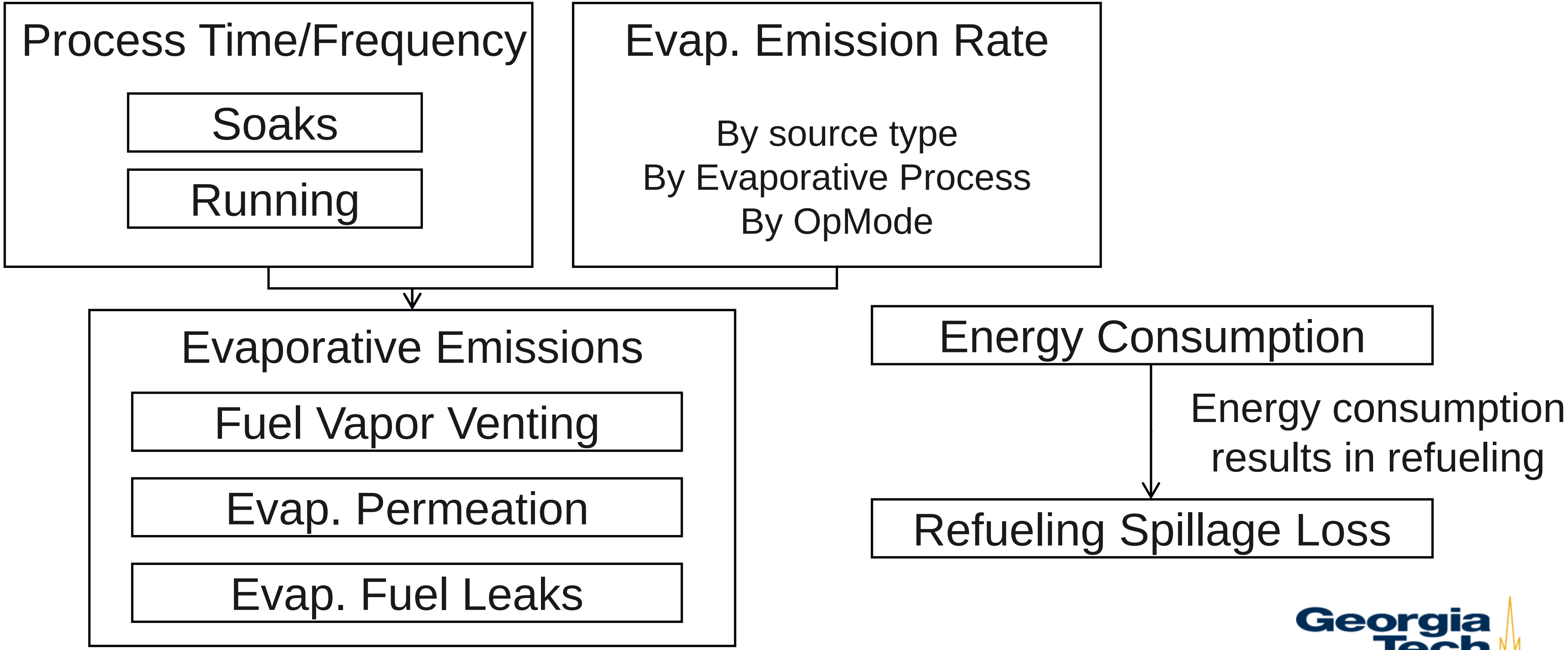
Source: EPA. Evaporative Emissions from On-road Vehicles in MOVES2014

- MOVES does not model emissions from non-fuel sources (washer fluids, paints, plastics, rubber, etc.)

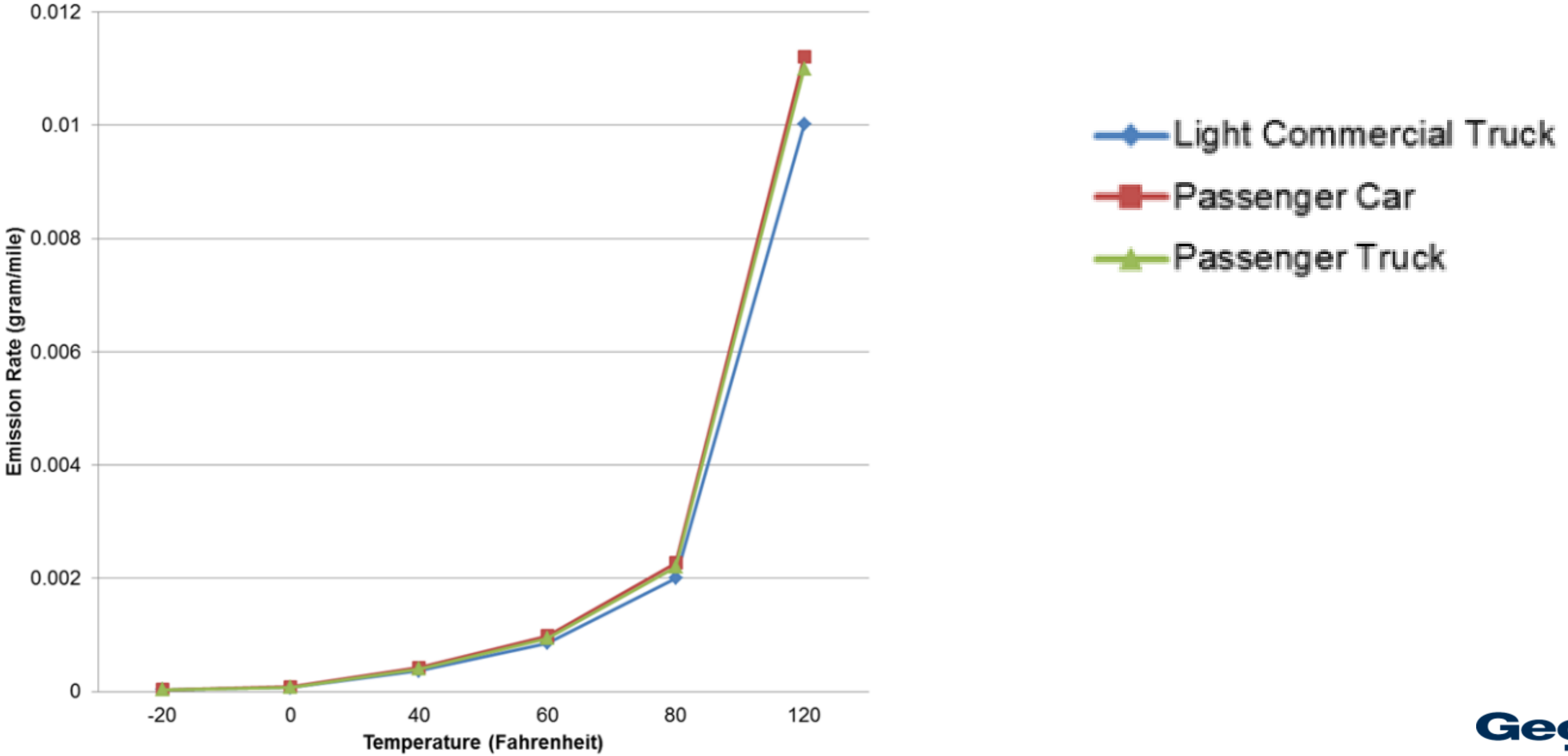
Evaporative Emissions

- Hydrocarbon vapor emissions:
  - During vehicle operation
  - After turning off a vehicle (hot soak emissions)
  - While parked (exposure to ambient temperature change)
  - During refueling (vapor loss and spillage)
  - From non-fuel sources, such as windshield washer fluid, paints, plastics, and rubber
- Evaporative emissions do not directly involve combustion
- Account for a significant portion of hydrocarbon emissions, especially from gasoline vehicles (vs. diesel)

Evaporative Emissions Modeling in MOVES



Evaporative Permeation - VOC Temperature Sensitivity from MOVES



Noel, G and R. Wayson, (2012) MOVES2010a Regional Level Sensitivity Analysis. Volpe National Transportation System Center

MOVES Summary

- MOVES is required for all regulatory modeling
  - Emission inventories for SIPs
  - Transportation/air quality conformity
  - Etc.
- Can be applied at any scale with knowledge of:
  - Fleet composition (regional or link-by-link)
  - On-road operating conditions (regional or link-by-link)
  - Environmental conditions (temp., humid., etc.)
  - Fuel specifications and I/M program