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Framework and Demonstration of Simulations of Environmental Impacts from Traffic on Highway Construction Work Zones

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Partnered Pavement Research Center (PPRC) Project Numbers 4.54 (DRISI Task 2718) and
4.66 (DRISI Task 3191): Environmental Life Cycle Assessment Updates and Applications

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16. ABSTRACT

The objective of this study was to develop a framework for determining the fuel use and environmental impacts caused by construction work zones (CWZs) on a range of vehicles and to produce initial calculations of these impacts by modeling traffic closure conditions for highway maintenance and rehabilitation (M&R) activities. The framework was developed and demonstrated in several scenarios. The study included three common highway categories—freeways, multi-lane highways, and two-lane highways—and common California vehicle types. The framework uses realistic drive cycle values and CWZ operation scenarios as inputs to the simulation software *MOtor Vehicle Emission Simulator (MOVES)* to estimate total fuel consumption and air pollutant emissions. In this study, the framework was demonstrated using three CWZ operations under different traffic congestion levels: light, medium, and heavy.

Fuel consumption and pollutant emissions results obtained for the CWZ operation scenario with and without congestion were compared with those for a no-CWZ, no-congestion scenario. In the simulation results for a freeway with a CWZ and heavy congestion, fuel consumption increased by 85% and the CO_2 equivalent (CO_2-e) emissions increased by 86%, NO_x by 62%, SO_x by 85%, and $PM_{2.5}$ by 128%. In the multi-lane highway scenarios, fuel consumption increased by 85%, and CO_2-e emissions increased by 88%, NO_x by 75%, SO_x by 87%, and $PM_{2.5}$ emissions by 129% for a CWZ with heavy congestion. Lessening traffic congestion in a CWZ from heavy (average speed 5 mph) to medium (average speed 25 mph for a freeway section and 15 mph for a multi-lane road section) reduced fuel consumption by 40% on a freeway and 33% on multi-lane highway.

This study also included use of a pilot car in a CWZ on a two-lane road. This approach was undertaken to estimate the possible benefits of different CWZ lane closure strategies and traffic management plans. The pilot-car operation scenario results indicate that a one-lane closure with pilot-car operation on a two-lane road might consume 13% more fuel because of idling time and the slow movement of vehicles following the pilot car. This scenario generated emissions increases of 10% for CO_2-e, 14% for NO_x, 13% for SO_x, and 65% for $PM_{2.5}$.

The results of these scenarios indicate that the impacts from heavy vehicles far exceed those from smaller vehicles in CWZs. Phase 2 of the study will develop methods for pavement management, conceptual evaluation, and project design that consider construction closures by implementing this life cycle assessment framework. These methods will also be used in studies to evaluate pavement design lives (20 years versus 40 years) and pavement selection for truck lanes and in-place recycling and to evaluate lane closure schedules and tactics to minimize CWZ impacts on highways by using project-specific traffic congestion levels.

17. KEY WORDS
fuel consumption, greenhouse gas, life cycle assessment, air pollutant

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It is recommended that the framework developed in this study be extended and then included in the *eLCAP* life cycle assessment software.

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Wang, T., Lee, I.S., Harvey, J., Kendall, A., Lee, E.B., and Kim, C. 2012. *UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance* (Research Report: UCPRC-RR-2012-02). Davis and Berkeley, CA: University of California Pavement Research Center.

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LIST OF ABBREVIATIONS

APU	Auxiliary power unit
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CH_4	Methane
CWZ	Construction work zone
EMFAC	EMission FACtor
GHG	Greenhouse gas
GREET	Gases, Regulated Emissions, and Energy use in Technologies
HDT	Heavy-duty truck
IRI	International Roughness Index
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LDT	Light-duty truck
M&R	Maintenance and rehabilitation
MOVES	Motor Vehicle Emission Simulator
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
PC	Passenger car
$PM_{2.5}$	Particulate matter with diameters less than 2.5 microns
PPRC	Partnered Pavement Research Center
PTW	Pump-to-wheel
SO_x	Sulfur oxides
SUV	Sport utility vehicle
WTP	Well-to-pump
WTW	Well-to-wheel

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

PROJECT OBJECTIVES

This study is a continuation of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.37 (Life-Cycle Assessment). The goal of this project is to develop a framework and continue updating and applying environmental life cycle assessment (LCA) procedures to improve the sustainability of pavement operations in California. This goal will be achieved by performing the following tasks:

- Task 1: Update the LCA models with new inventories, processes, and models (Phase 1).
- Task 2: Develop a framework for applying LCA and demonstrate it (Phase 1).
- Task 3: Evaluate design lives and pavement selection for truck lanes (Phase 2).
- Task 4: Support the development of better data collection methods for Caltrans and for industry (Phase 2).
- Task 5: Prepare technical memoranda documenting the study and its results (Phase 1 and 2).

The study presented in this technical memorandum completes Tasks 1, 2, and 5. This study's objective was to develop an LCA framework for analyzing the fuel use and environmental impacts of vehicles traveling in construction work zones (CWZs) and to produce initial calculations showing the impact of CWZs by modeling traffic closure conditions for highway maintenance and rehabilitation projects. This study developed an LCA framework and demonstrated its use in simulations of several example cases that include three common California highway categories and four common California vehicle types.

The results of the study will be used to consider construction closures in an LCA framework developed for pavement management, conceptual evaluation, and project design. The results of simulations will also be used in studies to evaluate pavement design lives (20 years versus 40 years) and pavement selection for truck lanes and in-place recycling and to evaluate lane closure schedules and tactics for minimizing the impacts of CWZs on highways with project-specific traffic congestion levels.

INTRODUCTION

1.1 Project Background

Surface transportation is a major contributor to global warming and climate change in the United States. In California in 2015, on-road trucks and cars contributed 34% of all the carbon dioxide (CO_2) emitted into the air *(1)*. To reduce greenhouse gas (GHG) emissions from all sources throughout the state*,* the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006 *(2)*. Many subsequent studies undertaken to accomplish the bill's objectives have focused on reducing GHG emissions across various industrial sectors. Decisions related to pavement construction, rehabilitation, and maintenance within the context of AB 32 will affect two sectors: transportation and industry. Impacts to the transportation sector will result from decisions about vehicle fuel use and fuel economy standards because the GHG emissions associated with these will be affected by pavement conditions and operations, by vehicle use for hauling pavement materials, and by demolition. Impacts to the industry sector will result whenever pavement material production involves oil extraction and refining, cement manufacturing, aggregate mining, and the activities of equipment used in construction and recycling.

Any road area where construction or maintenance activity occurs is referred to as a construction work zone (CWZ) *(3)*. CWZs that affect traffic movement may cause traffic delays, congestion, and accidents *(4).* Almost $124 billion was lost in the United States in 2013 due to traffic congestion, and this amount is projected to increase to $186 billion by 2030 *(5).* According to a 2004 study by the American Highway Users Alliance *(6),* almost 15% of total congestion is due to CWZs*,* which means that in 2013 a loss of approximately $28 billion could be directly attributed to them (if that percentage has not increased since the time of that study). Therefore, it is important to evaluate different work zone scenarios with different congestion levels in terms of cost, energy, and environmental impacts, both to lessen traffic delays and accidents and to find more efficient ways to conduct construction and maintenance.

1.2 Literature Review

During the literature review, several research articles on CWZ scenarios were found that looked at cost *(7,8,9,10).* However, not much research was found on the environmental impacts of CWZs.

Numerous studies have demonstrated that a life cycle assessment (LCA) approach is useful to comprehensively evaluate the total environmental burdens created by a product/system and to reduce the risk that a policy or strategy for dealing with environmental problems might produce unintended negative consequences. In a study summarized in the FHWA sustainable pavements reference document *(11)* and performed by the University of Illinois *(12),* an LCA for a 7.6 lane-mile (ln-mi) road section was performed for three CWZ cases. In Case 1, the

CWZ was divided into four equal-sized work zones and a nighttime (9 p.m. to 5 a.m.) closure was assumed. In Case 2, the CWZ was divided into halves and a 16-hour (10 p.m. to 2 p.m.) closure was assumed. In Case 3, a 32-hour closure—stretching over a 24-hour period from 9 p.m. to 9 p.m. and then 9 p.m. to 5 a.m. the following day—was assumed for an entire 7.6 ln-mi CWZ section. The study defined a drive cycle as a repeated, second-by-second sequence of a vehicle's speed profile that reflects a driving pattern under a specific traffic flow condition. Drive cycles contain a degree of randomness, and repetition of a particular cycle is rarely observed, even under real situations with the same traffic conditions. The drive cycles were generated using the Kentucky Highway User Costs Program model, and the US Environmental Protection Agency's (US EPA) *MOtor Vehicle Emission Simulator* (*MOVES*) was used to evaluate the scenarios in terms of energy and CO_2-e. (Note: *MOVES* refers to "drive cycles" as a "drive schedule." In this technical memorandum, the term "drive cycle" is used in all cases.) The study found a slight increase in energy use and emissions as the CWZ's length increased (Case 2 to Case 3). However, the results of Case 3 also showed drastic increases, producing 4.9 times more CO_2-e than Case 1 and 4.4 times more than Case 2 and consuming 5.2 times more energy than Case 1 and 4.5 times more than Case 2 *(12).*

Two previous UCPRC studies examined the environmental impacts of work zones. The first was a project-level environmental impact study that evaluated the fuel consumption and pollutant emissions of selected pavement maintenance and rehabilitation (M&R) activities, but that study considered only nighttime construction treatments that did not cause significant CWZ congestion *(13)*. A second study with a network-level analysis aimed to optimize International Roughness Index (IRI) values to minimize GHG emissions, but this analysis also considered only nighttime construction *(14)*.

A wider range of treatments and work zone scenarios needs to be considered for a couple of reasons. First, the additional funding becoming available for the California state highway network will lead to more rehabilitation projects that cannot be completed only using nighttime closures. Second, the need to reconstruct or rehabilitate existing pavements with 20- to 40-year design lives has grown, and these projects often require treatments that create CWZ-related congestion that is greater than the treatments considered in the previous studies. The research presented in this current study develops a framework and presents initial results for estimating CWZ congestion and its effects on vehicle fuel economy.

1.3 Goal and Objectives

This study is a continuation of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.37 (Life-Cycle Assessment). The goal of this project is to develop a framework and continue updating and applying environmental LCA procedures to improve the sustainability of pavement operations in California. This goal will be achieved by performing the following tasks:

- Task 1: Update the LCA models with new inventories, processes, and models (Phase 1).
- Task 2: Develop a framework for applying LCA and demonstrate it (Phase 1).
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- Task 4: Support the development of better data collection methods for Caltrans and for industry (Phase 2).
- Task 5: Prepare technical memoranda documenting the study and its results (Phase 1 and 2).

The study presented in this technical memorandum partially completes Tasks 1, 2, and 5. The study's objectives are to develop an LCA framework for analyzing the fuel use and environmental impacts of vehicles traveling in CWZs and to produce initial calculations showing the impact of CWZs by modeling traffic closure conditions for highway M&R projects. This study develops an LCA framework and demonstrates its use in simulations of several example cases that include three common California highway categories and four common California vehicle types.

The results of this study will be used in future work to consider construction closures in an LCA framework developed for pavement management, conceptual evaluation, and project design. The results of simulations will also be used to evaluate the role of construction closures on pavement management, conceptual design evaluation, and project design in the LCA framework. The results of this study will also be used in future studies to evaluate pavement design lives (20 years versus 40 years) and pavement selection for truck lanes and in-place recycling and to evaluate lane closure schedules and tactics for minimizing the impacts of CWZs on highways with project-specific traffic congestion levels.

1.4 Scope of Study

The aim of this study is to develop a framework that can analyze changes to LCA indicators in different CWZ scenarios. The proposed framework will allow comparisons of fuel consumption and the environmental impacts of different California-specific CWZ scenarios involving varied vehicle types, drive cycles, and congestion levels. The scenarios considered include freeways, multi-lane highways, and two-lane highways under low to high traffic congestion levels. The environmental impacts considered in this study include fuel consumption by fuel source type (gasoline or diesel), GHG emissions, fine particulate matter emissions ($PM_{2.5}$), oxides of nitrogen (NO_x), and sulfur dioxide (SO_2) emissions. This study used already available tools and databases to evaluate the CWZ scenarios. This technical memorandum documents Phase 1 of this study, the scope of which is shown in Figure 1.1. Phase 2 will be continued in a follow up study.

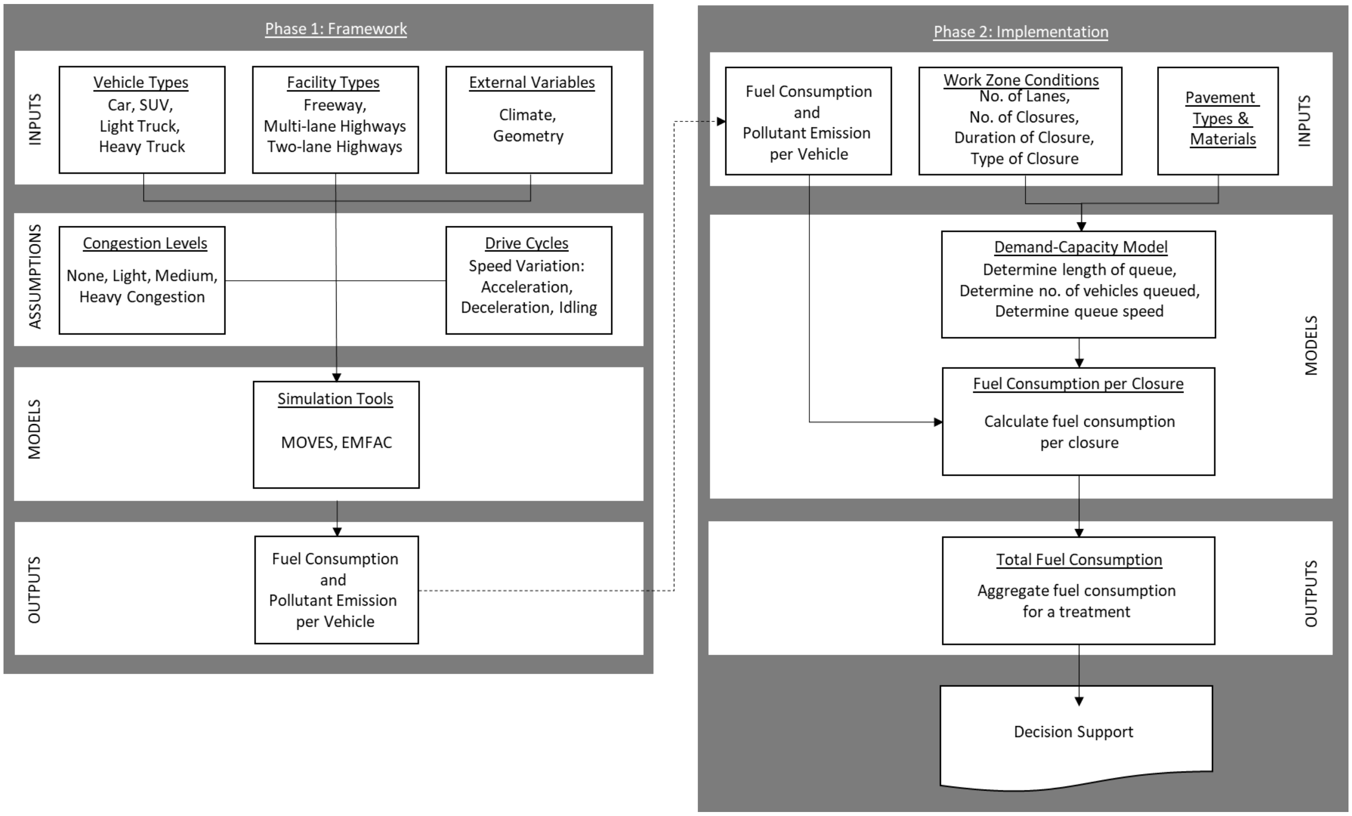

Figure 1.1: Schematic of the overall study's approach, showing Phase 1 (documented in this technical memorandum) and Phase 2 (to be completed subsequently).

1.5 Study Approach

This study used the US EPA's *MOtor Vehicle Emission Simulator* (*MOVES*) program to estimate fuel consumption and pollutant emissions from the combustion of the fuel (diesel and gasoline) by vehicles. The research used a project-level simulation approach (simulation of individual vehicles), allowing *MOVES* to perform estimates at different analysis levels, such as vehicle type and traffic congestion level *(15)*.

Different driving behaviors, vehicle fuel types, fuel qualities, and road network topographies *(16,17,18)* result in unique drive cycles, fuel use, and emissions for every geographic location. Therefore, the *MOVES* user guide instructs users to provide localized inputs, such as observed drive cycles, to the program to obtain an accurate analysis. The US EPA also provides documents that describe most of the criteria and factors related to drive cycles, but information about how to collect and develop drive cycles is scarce and no actionable guide exists for developing local emissions test data *(19,20)*.

The database-centered structure of *MOVES* gives users flexibility to control local parameters. The drive cycle input reflects different vehicle operations and traffic conditions. In a *MOVES* simulation, a drive cycle provides a repeatable sequence of a vehicle's speed profile over time.

The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model developed by Argonne National Laboratory *(21)* was used to determine the impacts of the production of fuels (gasoline and diesel). The study used the generated impacts to map the total life cycles of fuels in the CWZ scenarios of this study.

The following tasks were completed in Phase 1 of this study to develop a framework and determine initial values for the effects of CWZs on the impact indicators of interest documented in this technical memorandum (also shown in Figure 1.1):

(1) Determine vehicle types, facility types, and external variables.
(2) Establish scenarios and collect drive cycles per vehicle type.
(3) Run *MOVES* and *EMission FACtor (EMFAC)* simulations for scenarios.
(4) Summarize simulation outputs (fuel consumption and pollutant emissions).

Phase 2 of this study will implement the results gathered in Phase 1 for estimating the total environmental impacts of a road maintenance activity. A variety of CWZ conditions, pavement types, and materials affect the results of total fuel consumption and pollutant emissions per maintenance activity. The application tool developed in Phase 1 will allow users to estimate total fuel consumption and pollutant emissions for each CWZ condition and will provide support for selecting a strategy that minimizes environmental impacts from maintenance activities.

2 VARIABLES AND EXPERIMENT DESIGN

This chapter describes the CWZ types, environmental impact indicator categories, simulation models and assumptions, and scenario factorial considered in this study.

2.1 Construction Work Zone Types

Two California-specific CWZ types were considered in this study:

- Partial lane closure for a multi-lane freeway or highway
- One full-lane closure on a two-lane highway—stop and slow signs or pilot-car operation

For the purposes of this technical memorandum, when the term CWZ is applied to a freeway or multi-lane road, it refers to the lane that is closed (or will be closed) and all the adjacent lanes that carry traffic in the same direction as the closed lane. But, when the term is applied to a two-lane road, it includes the lane that carries traffic in the opposite direction as well. References to the CWZ's length apply to the roadways both within the closure and outside it.

2.1.1 Partial Lane Closure for a Multi-Lane Freeway or Highway

Partial lane closure operations are commonly used for M&R activities on freeways and other multi-lane highways to minimize traffic flow interruption during lane closures, to provide access for construction workers, and to maximize worker and road user safety. Figure 2.1 illustrates a typical configuration of a partial lane closure operation in a CWZ. Traffic capacity in a CWZ is usually less than the roadway's capacity under normal operating conditions because when a CWZ is set up, the lane loss lowers the roadway's traffic capacity. When upstream traffic demand exceeds this reduced capacity, a queue will develop at the start of the CWZ. These reduced capacities can be as low as 1,500 passenger cars per hour per lane (pcphpl) for a two-lane operation and 1,200 pcphpl for a single-lane operation, compared with observed normal traffic capacities as large as 2,300 pcphpl for a two-lane operation and 1,800 pcphpl for a single-lane operation. There are several possible contributors to reduced traffic capacity in CWZs:

- Fewer open traffic lanes
- Narrowed open traffic lane widths due to increased construction site space or the addition of lanes to the remaining roadway
- Reduced posted speed limit in the CWZ (e.g., a speed limit 10 mph lower than a non-CWZ operation speed limit to increase safety)
- Driver distractions caused by construction activities and barrier rails

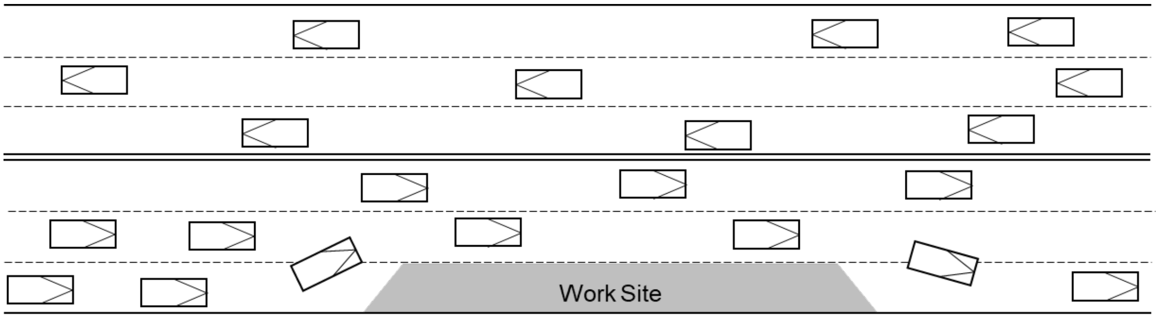

Figure 2.1: Partial lane closure configuration on a multi-lane freeway or highway.

2.1.2 One Full-Lane Closure on a Two-Lane Highway—Stop and Slow Signs or Pilot-Car Operation

For two-lane highways (one lane in each traffic flow direction), the full closure of one lane will significantly impact the traffic flow in both directions since one lane must be shared for traffic operations in both directions. Although not always possible, M&R activities in this case are usually performed during lower-traffic hours. For short-term CWZs, temporary electronic traffic signals or maintenance crews handling stop and/or slow signs are commonly used. For longer-term CWZs or longer-length CWZs, a pilot car is commonly used. In this situation, maintenance crew members at one end of the CWZ stop the traffic while a pilot car escorts vehicles in the other direction through the CWZ, shown in Figure 2.2.

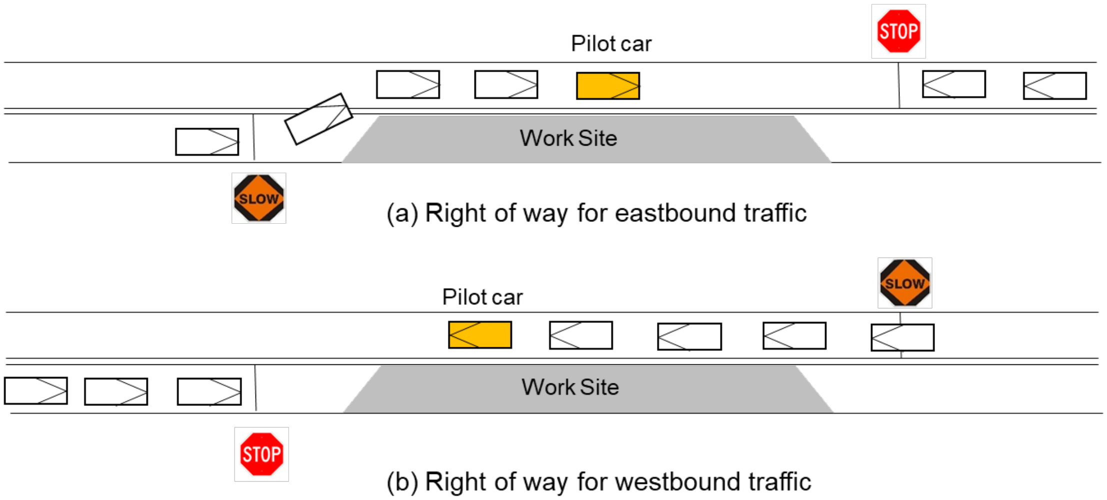

Figure 2.2: Lane closure configuration with a pilot-car operation for a two-lane highway.

2.2 Environmental Impact Indicator Categories

2.2.1 Air Pollutant Emissions

Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are all emitted during the combustion of petroleum-based fuels by the internal combustion engines of vehicles. These gases trap heat in the atmosphere and contribute to global warming. The *MOVES* software program treats these emissions (CO_2, CH_4, and N_2O) in terms of the unit CO_2-equivalent (CO_2-e), a parameter that combines the emissions and their contributions to global warming potential. In calculations where these different emissions are combined, they are expressed in terms of the mass unit CO_2-e, which is 1 mass unit of CO_2. CH_4 is considered equivalent to 25 mass units of CO_2, and N_2O is considered equivalent to 298 mass units of CO_2 *(22)*. These values are based on the gases' relative contributions to global warming.

Other important pollutant emissions considered in this study are oxides of nitrogen (NO_x), sulfur dioxides (SO_2), and fine particulate matter smaller than 2.5 microns ($PM_{2.5}$) because they contribute to respiratory problems, including bronchitis, asthma, and emphysema. NO_x is an important pollutant emission because of its major photochemical ozone creation potential, meaning that it forms ground level ozone when it reacts with volatile organic compounds in the presence of sunlight. SO_2 emissions are produced by fossil fuel combustion engines like those in heavy vehicles and other equipment that burn high sulfur-content fuels, and they also can harm the human respiratory system and cause breathing difficulties, especially in children and the elderly. $PM_{2.5}$ particles are smaller than 2.5 microns and are light enough to stay in the air longer than heavier particles (e.g., particles between 2.5 and 10 mm, PM_{10}). They are dangerous because they can cause chronic heart and lung diseases when humans inhale them. During vehicular operations, $PM_{2.5}$ is generated from exhaust, brake wear, and tire wear.

2.2.2 Life Cycle Approach for Fuel (Gasoline and Diesel)

In a life cycle approach, the vehicle fuel life cycle is typically calculated for two stages of the life cycle (well-to-pump and pump-to-wheel), which together make up the complete life cycle (well-to-wheel).

The two fuel life cycle stages are the following:

- Well-to-pump (WTP) analysis: All the processes and related emissions from extraction of the crude oil, transportation to the refinery, the refinery process and, transportation to fueling stations are included in the analysis. This stage can also be called a cradle-to-gate analysis.
- Pump-to-wheel (PTW) analysis: The combustion of the fuel by the vehicle during the use stage of the life cycle is analyzed.

The complete life cycle is the following:

- Well-to-wheel (WTW) analysis: For a complete life cycle analysis, also referred to as a cradle-to-grave analysis, the calculations include all the processes of the well-to-pump and pump-to-wheel stages.

MOVES only reports the PTW analysis results. For the results to be complete, a WTP analysis for gasoline and diesel must be performed.

2.2.3 Fuel Inventory (Well-to-Pump)

To carry out the WTP analysis for gasoline and diesel fuel, three different inventories were used and data from them were used in the following ways:

(1) Exporting life cycle inventories (LCIs) from the *GaBi*[1] fuel (diesel and gasoline) models and adding them to the LCIs from a model for tanker trucks that transports fuels from refinery to fuel stations (pump) for an average distance of 100 miles.
(2) Replacing the US electricity mix in the *GaBi* models with the 2017 California electricity mix model developed for the study, and adding LCIs of tanker truck transportation for 100 miles (from refinery to pump).
(3) Exporting results from GREET *(21)*.

The *GaBi* software was used to create models of gasoline and diesel fuel production and their transportation by tanker truck. On average, the transport distance between the refinery and the fuel stations was assumed to be 100 miles. This assumption was based on the location of the refineries in California and a rough estimate of the distance that fuels must travel to the nearest refinery. California's electricity mix contains low-emission, nonrenewable energy resources, such as natural gas, and zero-emission renewable energy sources, such as solar and wind; therefore, the total emissions calculated are much lower than the US average electricity mix. For a comparison, the WTP results for the two fuels using three different inventories are shown in Table 2.1. The WTP inventory used in this study is from the GREET model as this is the model used most, and the results of this study can be compared with other studies.

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[1] https://gabi.sphera.com/america/index/.

Table 2.1. Well-to-Pump Analysis of the Fuels

	Units	GaBi (Using CA Electricity Mix)		GaBi (Using Average US Electricity Mix)		Greet-CA	
		1 Gallon Gasoline	1 Gallon Diesel	1 Gallon Gasoline	1 Gallon Diesel	1 Gallon Gasoline	1 Gallon Diesel
Carbon dioxide equivalent (CO_2-e)	g	177	164	202	186	2,470	1,970
Nitrogen oxides (NO_x)	g	0.030	0.028	1.220	1.130	5.310	5.340
Sulfur dioxide (SO_2)[1]	g	1.520	1.400	1.760	1.630	3.390	2.960
Particulate matter ($PM_{2.5}$)	g	0.156	0.144	0.177	0.164	0.370	0.336

[1] SO_x in Greet-CA inventory is assumed to be SO_2.

2.2.4 Fuel Consumption (Pump-to-Wheel)

In *MOVES,* the unit kilojoules (kJ) is used to indicate energy consumption. However, for this current study, energy consumption was converted to fuel consumption in gallons, a more intuitive interpretation. Converting energy to fuel use requires values for instantaneous/total consumed energy, energy density of fuel, and fuel density. In this study, to obtain reproducible and comparable results, fuel density values from the *MOVES* default database were used: (1) for gasoline, an energy density of 43.488 kJ/g and a fuel density of 2,839 g/gal. and (2) for diesel, 43.717 kJ/g and 3,167 g/gal. *(22).* To enable comparison of the energy-fuel conversion factors, the resulting energy-fuel conversion factors from *MOVES* are presented in Table 2.2 along with factors from NCHRP Report 720 (*23*), the US Energy Information Administration, and bomb calorimeter and density tests performed by the UCPRC on fuels from the Sacramento area as part of another study in 2016 (*24*). It is likely that any differences between the energy-fuel conversion factors are mainly due to differences in the fuel density and fuel energy density of the fuels tested in each study. Those differences are in turn likely due to variability among the amounts of ethanol and/or other additives in the fuels tested, particularly in winter blends; that variability can result in fuel density and energy density variability.

Table 2.2: Energy Unit Conversion Factors from MOVES2014, NCHRP 720, 2012, and US EIA Consumption, 2017

Category	Energy-Fuel Conversion Factors (MJ/gal.)				
	MOVES2014[a]	NCHRP 720, 2012[b]	US EIA, 2017[c]	UCPRC, Summer[d]	UCPRC, Winter[d]
Gasoline	122.6	128.7	127.1	122.2	120.0
Diesel	138.5	151.4	145.0	135.8	135.8

[a] Source: US Environmental Protection Agency (2015) (*22*)
[b] Source: Chatti and Zaabar (2012) (*23*)
[c] Source: US Energy Information Administration (2021) (*24*)
[d] Source: Butt et al. (2022) (*25*)

2.3 Model Selection

Initially, *MOVES* and *EMFAC* models were both studied. *MOVES* is a US EPA tool that estimates fuel consumption and pollutant emissions *(26)*. *EMFAC* is a model developed by the California Air Resources Board that calculates statewide/regional emissions from motor vehicles in California *(27)*. The following sections describe the two models and discuss why the study selected one over the other.

2.3.1 MOVES Fuel Consumption and Pollutant Emissions Model

MOVES estimates emission rates and inventories by using a disaggregated approach *(15)* that allows the model to perform estimates at two different analysis levels: the county level and the project level. The county level model uses a macroscopic approach to compute an entire county's annual pollutant emissions. Annual vehicle miles traveled, county road network, and average vehicle speed—considering drive cycles—in the *MOVES* database are used to estimate annual pollutant emissions. The project-level model uses a microscopic approach to compute hourly pollutant emissions of a specific road segment or corridor, considering hourly traffic volumes, road distance, road gradient, and user-specified drive cycles to estimate hourly pollutant emissions *(15)*. The input values are described in Appendix A.

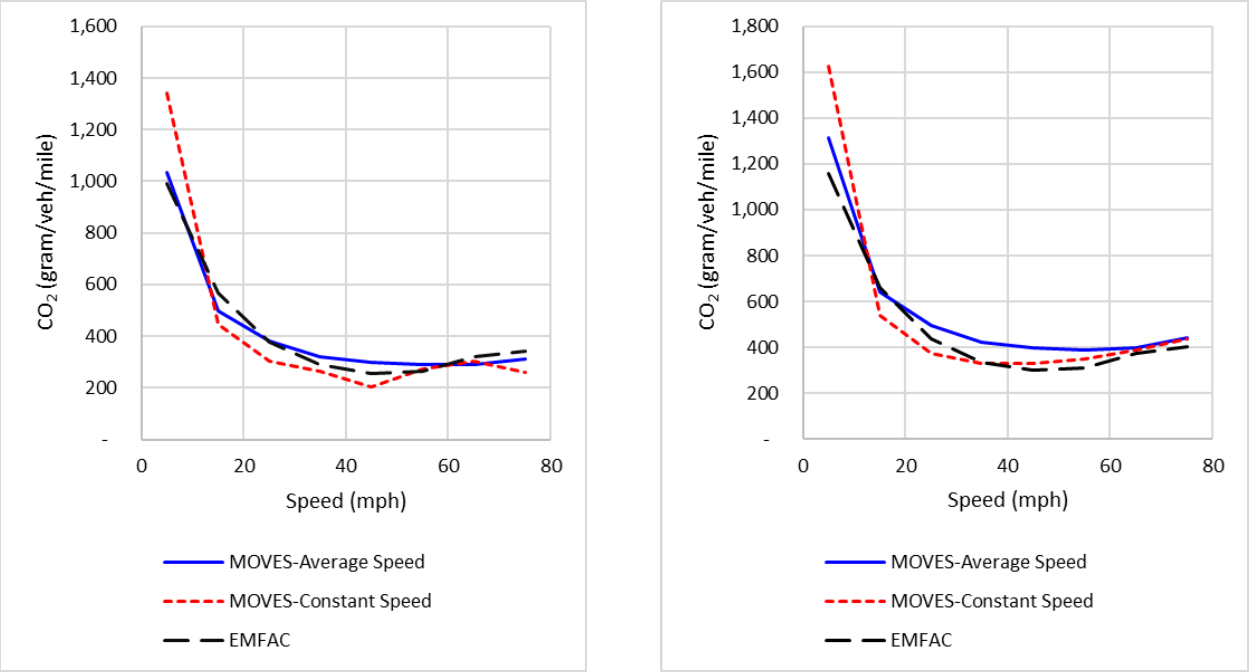
Although the most recent version of *MOVES* available, *MOVES2014a*, was used, it does not yet consider the diesel Tier 4 engine standards that introduced substantial reductions of NO_x (for engines above 56 kW) and particulate matter (for engines above 19 kW) *(22)*.

2.3.2 EMFAC

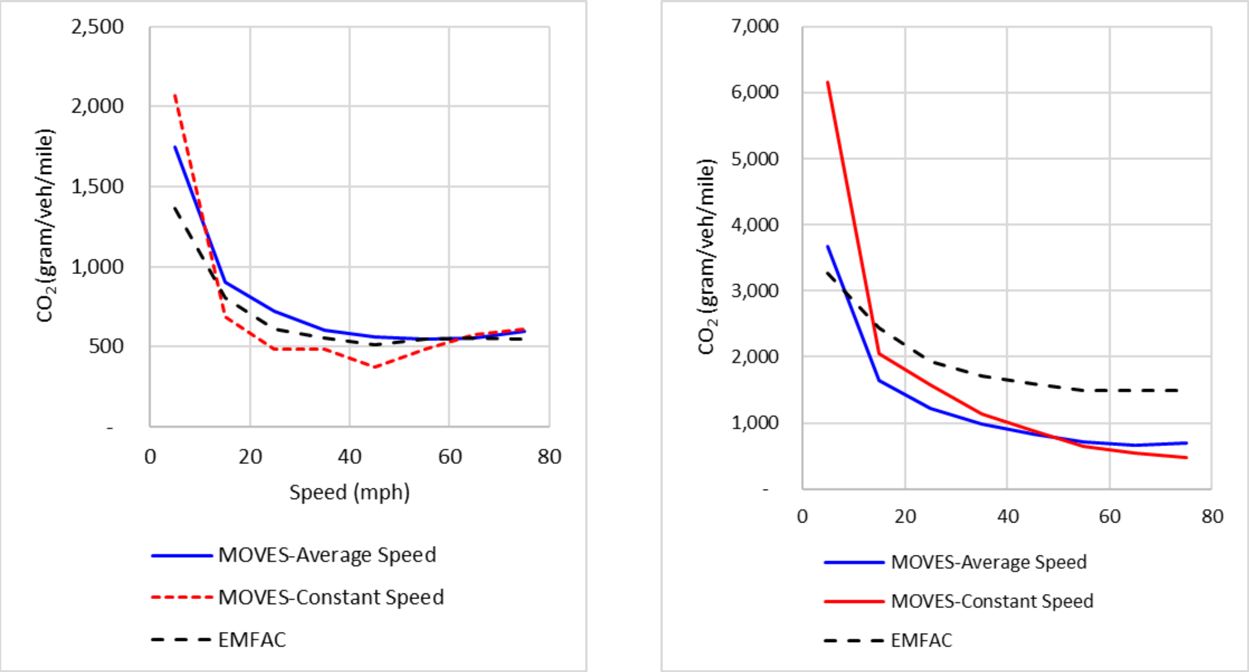
EMFAC2014 (27) includes travel activity data and emission rates for passenger cars and trucks, and it incorporates a function for developing vehicle age distributions and for forecasting future vehicle miles traveled.

2.3.3 Comparison of Models

Figure 2.3 shows a comparison of the CO_2 equivalents (CO_2-e) calculated by *MOVES2014a* using two speed settings (one using constant speed and the other using average speed, and both with the default drive cycles) and one calculated by *EMFAC2014* using constant speed. The CO_2 emissions for different vehicle types for a range of vehicle speeds were found to be very similar in *MOVES2014a* and *EMFAC2014,* shown in Figure 2.3. The emissions rates in terms of CO_2-e were generated using both constant speed and average speed, considering the different drive cycles associated with the four vehicle types in *MOVES*, and using *EMFAC* and its constant speed assumption for the four vehicle types (a gasoline-powered passenger car, a gasoline-powered sport utility vehicle, a light-duty diesel truck, and a heavy-duty diesel truck, shown in Table 2.3) under average speeds of 5 mph through 75 mph in 10 mph increments. The results in tabular form are presented in Appendix B. Further, comparisons of other emissions from the *MOVES* simulation—with constant speed and average speed and with the default drive cycles—and the *EMFAC* simulation with constant speed are also presented in tables in Appendix B.



(a) Passenger car (PC) **(b) Sport utility vehicle (SUV)**



(c) Light-duty truck (LDT) **(d) Heavy-duty truck (HDT)**

Figure 2.3: Comparison of CO_2 equivalents by speed for *MOVES* and *EMFAC*.

Table 2.3: Vehicle Type Comparison

Vehicle Types in This Study[1]	Vehicle Types in EMFAC		Vehicle Types in MOVES	
	Code	**Description**	**ID**	**Description**
Passenger Car	LDA	Passenger Car	21	Passenger Car
Sport Utility Vehicle	LDT1	Light-Duty Truck (GVWR<6,000 lb. and ETW<3,750 lb.)	31	Passenger Truck (personal use)
Light-Duty Truck	LHD1	Light Heavy-Duty Truck (GVWR 8,501 – 10,000 lb.)	32	Light Commercial Truck
Heavy-Duty Truck	MDV	Medium-Duty Trucks (GVWR 6,000 and 8,500 lb.)	52	Single Unit Short-Haul Truck

[1] Gasoline-fueled vehicles include a passenger car (PC) and a sport utility vehicle (SUV), whereas the light- and heavy-duty truck types (LDT and HDT) are diesel-fueled vehicles.

For the demonstration described in this technical memorandum, the results were calculated for the same geographic, seasonal, and climate conditions (Sacramento County; May 2017; temperature: 70°F [21°C]; humidity: 50%).

EMFAC2014 was not selected for this study for the following reasons:

(1) Unlike *MOVES,* which uses second-by-second drive cycles (at the project level), *EMFAC* uses a constant speed fraction profile per hour per vehicle type with 5 mph increments that does not consider accelerations and decelerations.

(2) *EMFAC* does not consider the fuel consumption and pollutant emissions that occur when a vehicle accelerates or decelerates while traveling in a queue under congestion and, in particular, under stop-and-start operations.

Because of the study's objectives, it was necessary to estimate fuel consumption and pollutant emissions for the scenario where a vehicle undergoes stop-and-start operations as it travels through a CWZ. Therefore, *MOVES* was used as it allows users to input drive schedules (the *MOVES*-specific term for drive cycles*)* when estimating fuel consumption and pollutant emissions for a project-specific scenario.

2.4 Modeling Assumptions for the Framework and Demonstration

In this study, traffic scenarios were simulated both with and without CWZ operations under various traffic congestion levels and without congestion, and the results for both a freeway and a two-lane highway were compared. The following are the assumptions used to develop the CWZ analysis framework.

2.4.1 Geographic Assumptions

California's Sacramento County was selected as the geographic region for the simulation framework demonstration. In *MOVES,* each geographical region has a combination of temperature and humidity associated with the selected month and hour. For the simulation, a temperature of 70°F (21°C) and a humidity of 50% were selected, which in *MOVES* corresponded to conditions on a May morning from 8:00 a.m. to 9:00 a.m. in the region. Although *MOVES* can consider grade changes for actual projects, a decision was made not to use the effects of vertical grade or to incorporate them in the study results.

2.4.2 Facility and Operation Type Assumptions

This study considered three major facility types: (1) a freeway, (2) a multi-lane highway, and (3) a two-lane highway. The CWZ cases that are considered include the typical lane closure approaches for freeways and multi-lane highways and for two-lane highways.

Partial Lane Closures on Freeways and Multi-Lane Highways

Partial lane closure operations were assumed for both a freeway and a multi-lane highway: a two-lane closure on a four-lane, one-direction freeway and a one-lane closure on a two-lane, one-direction multi-lane highway. The average travel speed upstream of a CWZ was assumed to vary under different traffic conditions: no congestion, light congestion, medium congestion, and heavy congestion. The average travel speed on a freeway was considered a 65 mph free-flow speed during the no-CWZ scenario and a speed of 55 mph when a CWZ was in operation. Multi-lane highways had either a 55 mph free-flow speed where there was no CWZ and a 45 mph free-flow speed where a CWZ was in operation, or a 45 mph free-flow speed in a CWZ-free area and a 35 mph speed where there was a CWZ operation. Both the 55 mph and 45 mph free-flow speeds for multi-lane highways were included in the simulation scenarios. Once vehicles passed through a CWZ, their average speed increased to the free-flow speed (that is, to the posted speed limit).

One Full-Lane Closure on a Two-Lane Highway—Stop and Slow Signs or Pilot-Car Operation

For these scenarios, it was assumed that either traffic crews managed stop-and-wait directional traffic or the CWZs were signalized electronically. For two-lane highways, two free-flow traffic conditions (free-flow speeds of 45 mph or 55 mph) were assumed for the no-CWZ operation and posted speed limits in the CWZ were assumed to be either 35 mph or 45 mph (10 mph below the posted speed limit).

2.4.3 Assumed Traffic Congestion Levels

No traffic congestion was assumed under the no-CWZ scenario. Four traffic congestion levels under CWZ operations were considered for the freeway and two-lane road:

- No congestion: free-flow speed (posted speed limit)
- Light congestion: average travel speeds of 45 mph for freeways and 35 mph for multi-lane and two-lane highways
- Medium congestion: stop-and-start conditions with an average travel speed of 25 mph for freeways and 15 mph for multi-lane and two-lane highways

- Heavy congestion: stop-and-start conditions with an average travel speed of 5 mph for freeways, multi-lane highways, and two-lane highways

2.4.4 Assumed Vehicle Types

For the *MOVES* simulation, four vehicle types were chosen to estimate air pollutant emissions and fuel consumption rates under specific road types and traffic conditions with and without CWZ traffic controls:

- Passenger car (PC): gasoline-powered passenger car
- Sport utility vehicle (SUV): gasoline-powered sport utility vehicle
- Light-duty truck (LDT): diesel-powered single truck
- Heavy-duty truck (HDT): diesel-powered combination truck

In each scenario, it was assumed that light-duty vehicle (passenger cars and SUVs) traffic consisted of a mix of 60% passenger cars and 40% SUVs. The proportions of trucks used in the freeway, multi-lane highways, and two-lane highway scenarios, as shown in Section 3.1.2, Section 3.2.2, and Section 3.3.2, were collected from the Caltrans annual truck count *(28).* The vehicle classes are presented in Table 2.3 in Section 2.3.

2.5 Drive Cycles

Fuel consumption varies as a vehicle's drive cycle changes because the frequency and intensity of accelerations governs the amount of fuel vehicles use. In addition, as congestion builds in a traffic queue, a vehicle's drive cycle is governed by both the congestion level in the queue and by the free-flow speed in the CWZ. Also, generally for vehicles traveling at the same average speed, fuel consumption under stop-and-start conditions is higher than at a steady speed. In the *MOVES* project-level simulation, vehicles traveled with specified drive cycles on the associated link.

To check the accuracy of the default *MOVES* drive cycles, *MOVES* simulations were run with the following three types of drive cycles under three traffic congestion levels:

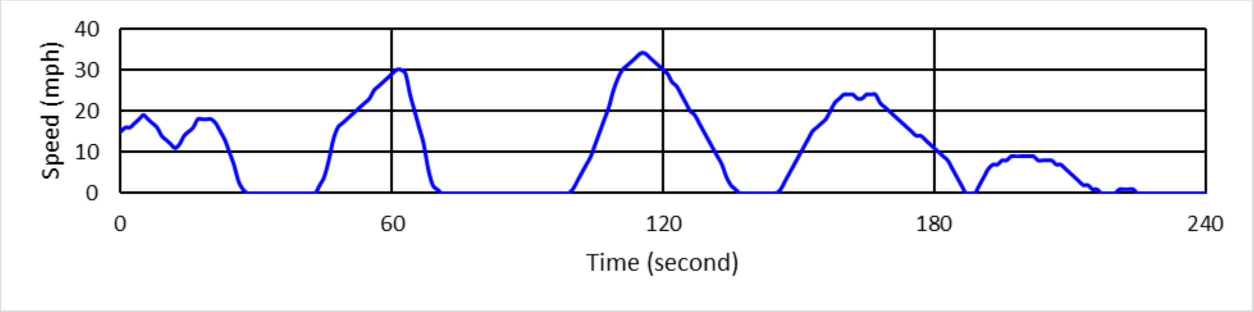
(1) *MOVES* default drive cycles for congested traffic
(2) *MOVES* constant speed
(3) Drive cycles collected in the field by the research team

The field drive cycles were collected from driving tests on a freeway with three traffic congestion levels:

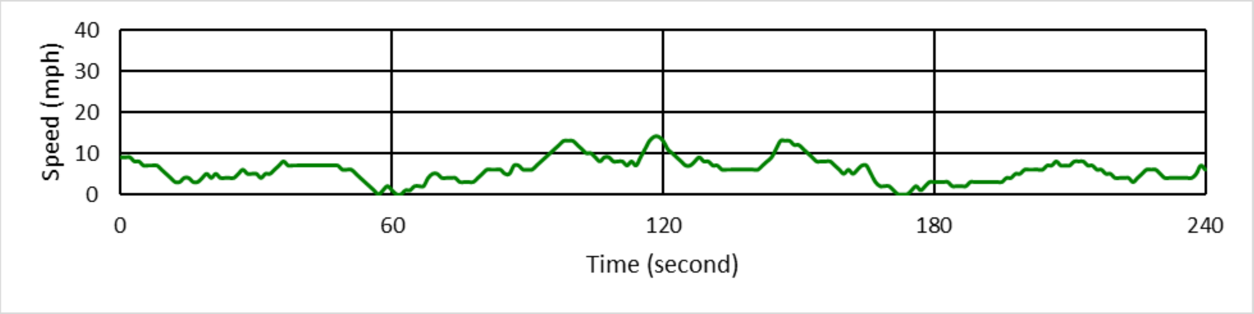
(1) Light congestion with an average speed of 35 mph
(2) Medium congestion with an average speed of 15 mph
(3) Heavy congestion with an average speed 5 mph with stop and start

To validate the *MOVES* default drive cycles for different vehicle types and travel speeds, the UCPRC collected drive cycle data on Interstate 80 in the Sacramento region. A UCPRC staff member drove a vehicle equipped with a global-positioning device behind a target vehicle (a light-duty truck or a heavy-duty truck) on a freeway section (Interstate 80 in Sacramento) at different times of the day to collect drive cycles at various speeds. While this occurred, a global-positioning-enabled device recorded the vehicle's location and speed each second as it traveled in a traffic queue under each traffic condition. The CO_2-equivalent (CO_2-e) emission amounts for the two drive cycles (*MOVES* default and field observed) were compared with the constant speeds (5, 15 and 35 mph) for each vehicle types (PC, SUV, LDT, and HDT). The CO_2-e results for the two drive cycles and the constant speed are shown in Appendix C.

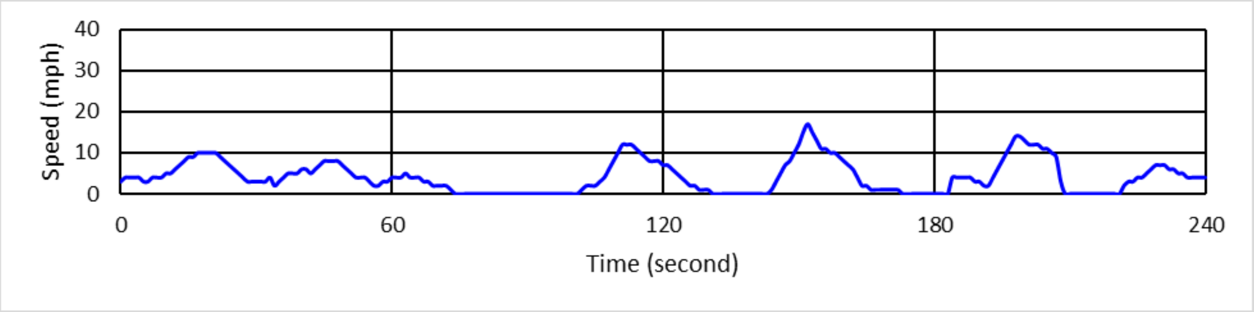
Figure 2.4, Figure 2.5, and Figure 2.6 show the *MOVES* drive cycles of three vehicle types (light-, medium-, and heavy-duty) and the field-collected drive cycles of a light-duty vehicle for three traffic congestion levels (light, medium, and heavy). The field-collected drive cycles were similar to the *MOVES* default drive cycles, except under heavy congestion at the 5 mph average speed, shown in Figure 2.4. Despite the difference for the light vehicle under heavy congestion conditions, a decision was made for the study to use the *MOVES* default drive cycles of each vehicle type with the associated congestion levels in the *MOVES* simulations because this project was not scoped to develop alternative drive cycles.



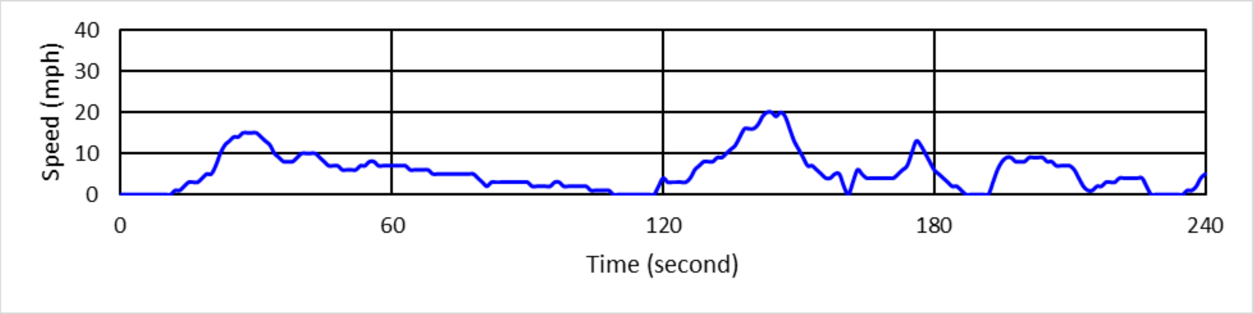
(a) *MOVES* light-duty vehicle



(b) Field light-duty vehicle

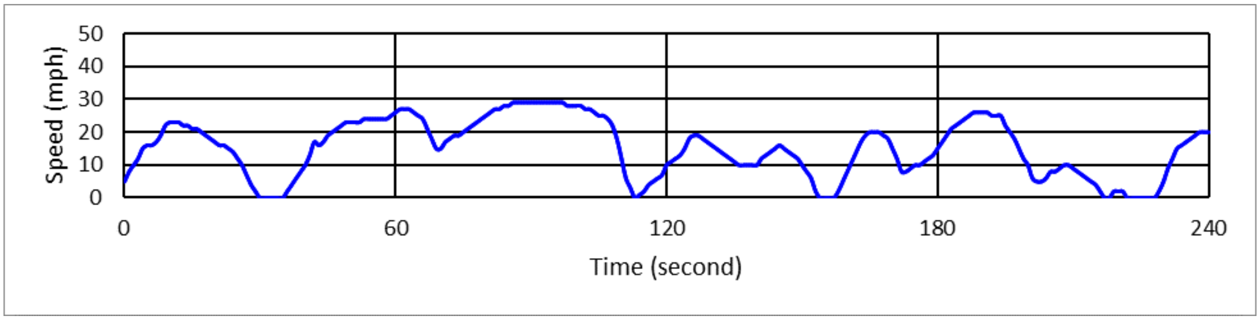


(c) *MOVES* medium-duty vehicle

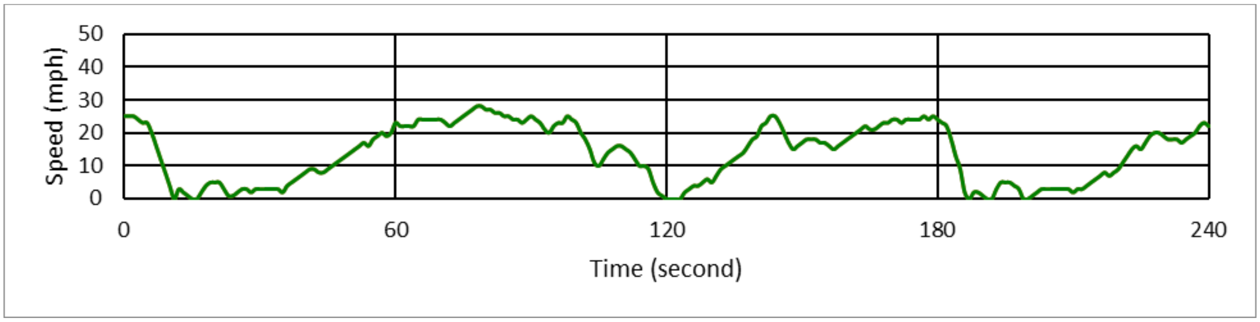


(d) *MOVES* heavy-duty vehicle

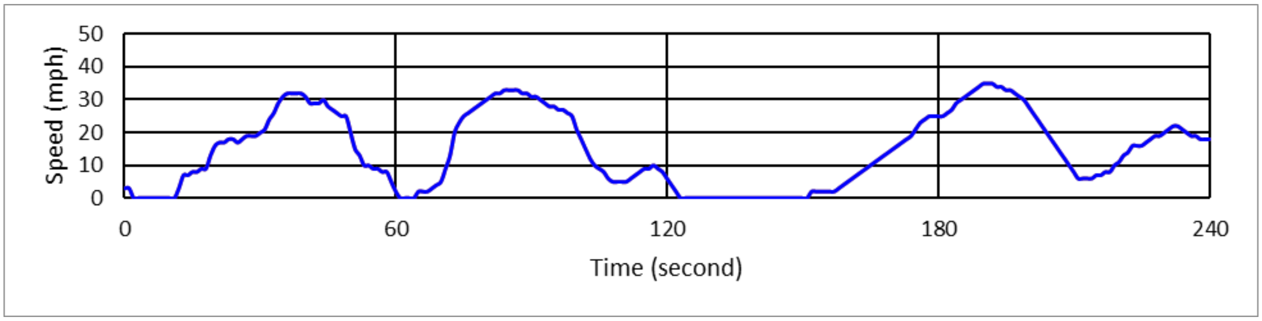
Figure 2.4: Comparison of drive cycles for *MOVES* and field observation (heavy congestion, average speed 5 mph).



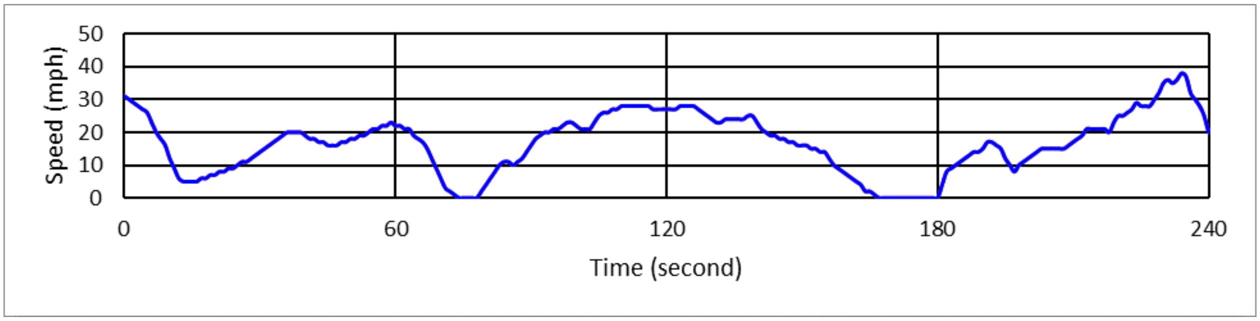
(a) ***MOVES*** **light-duty vehicle**



(b) Field light-duty vehicle

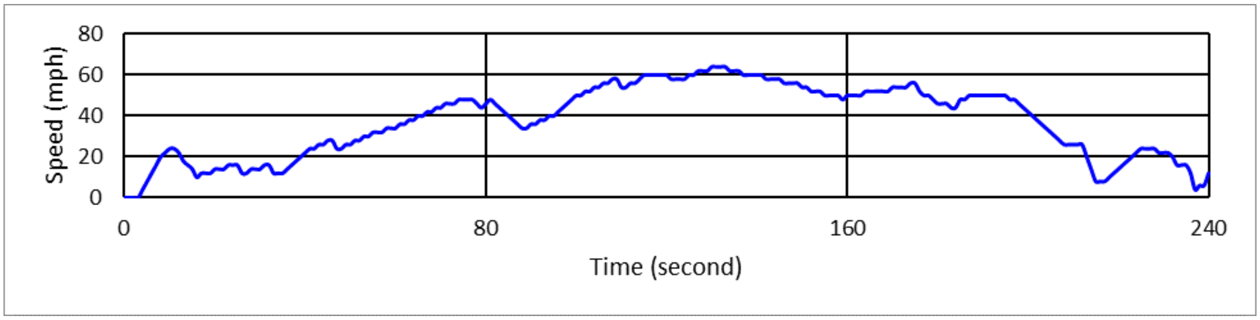


(c) ***MOVES*** **medium-duty vehicle**

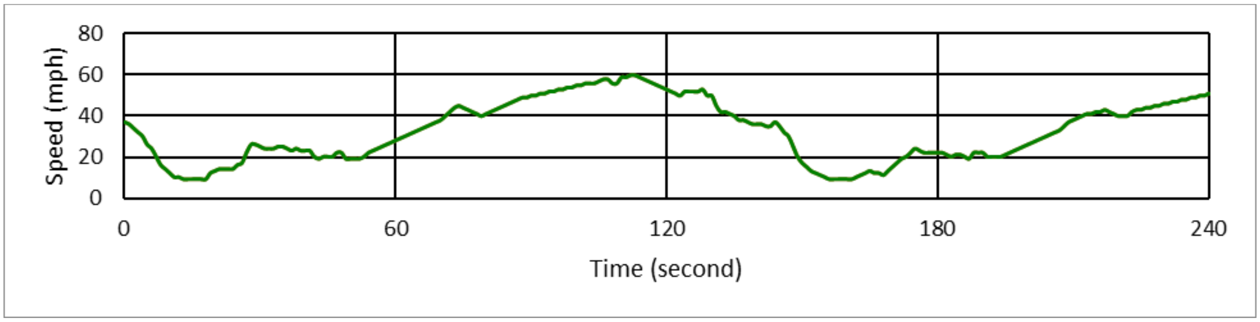


(d) ***MOVES*** **heavy-duty vehicle**

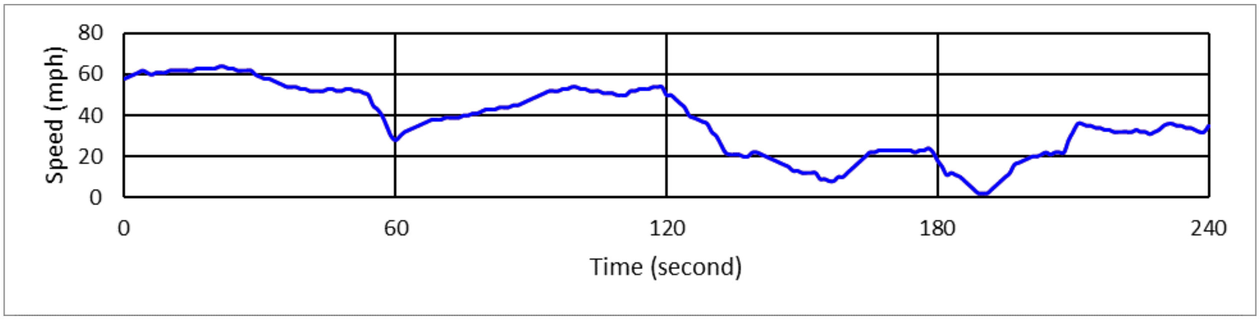
Figure 2.5: Comparison of drive cycles for ***MOVES*** **and field observation (medium congestion, average speed 15 mph).**



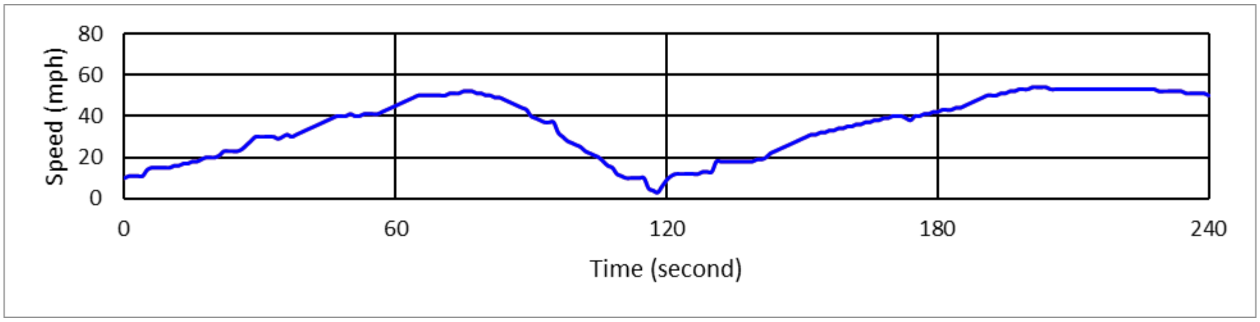
(a) *MOVES* light-duty vehicle



(b) Field light-duty vehicle



(c) *MOVES* medium-duty vehicle



(d) *MOVES* heavy-duty vehicle

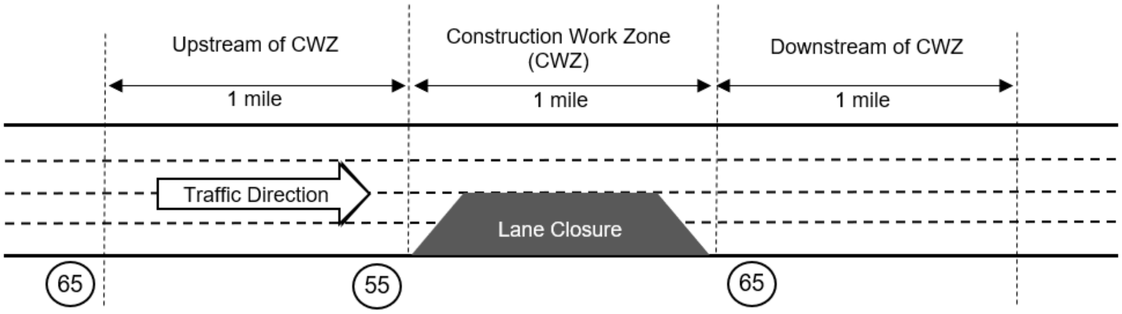
Figure 2.6: Comparison of drive cycles for *MOVES* and field observation (light congestion, average speed 35 mph).

2.6 Scenario Factorials for Demonstration

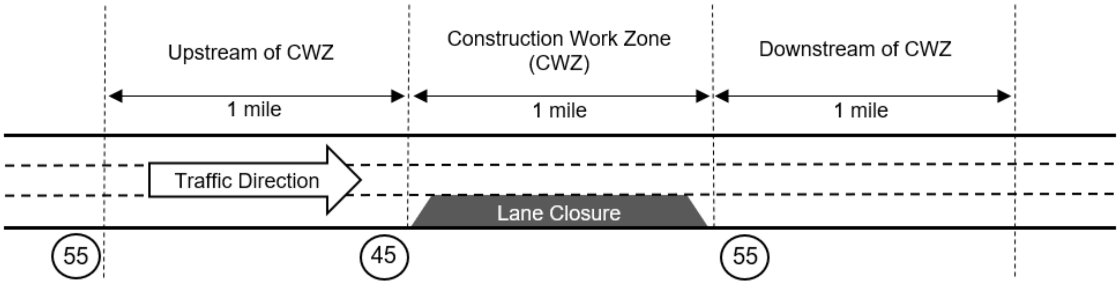
2.6.1 Partial Lane Closures on a Multi-Lane Freeway or Highway

To demonstrate the framework using *MOVES*, three simulation scenarios were created based on the selected road types and then run through the program to obtain estimates for single-vehicle fuel consumption under specific traffic operation methods and congestion levels. Then the simulations were repeated for each vehicle type, with *MOVES* calculating the total fuel amount each vehicle type consumed while traveling through a three-mile road segment under the different congestion conditions.

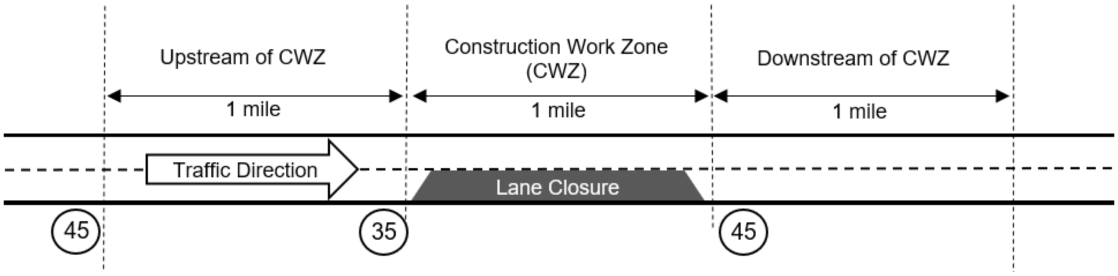
To demonstrate a partial lane closure on a freeway or multi-lane highway, a three-mile roadway segment was divided into three one-mile sections: a one-mile section upstream of the CWZ, a middle one-mile section with a lane closure where work was in progress (i.e., the CWZ), and a third one-mile downstream section to serve as the exit from the CWZ (see Figure 2.7). In all the scenarios, it was assumed that traffic traveled at free-flow speed in the downstream section.



(a) Freeway (posted speed limit: 65 mph)



(b) Multi-lane highway (posted speed limit: 55 mph)

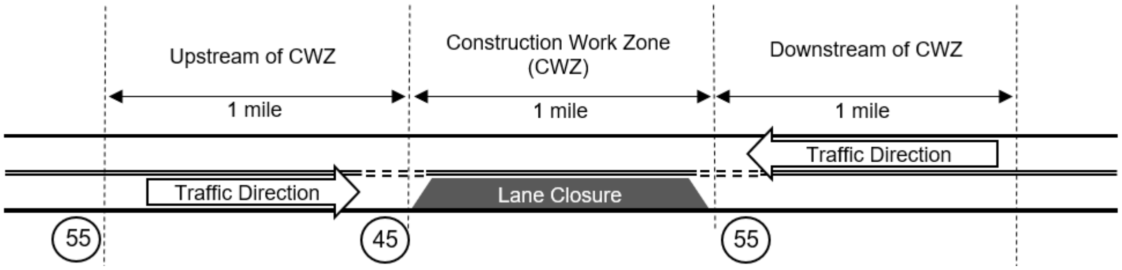


(c) Multi-lane highway (posted speed limit: 45 mph)

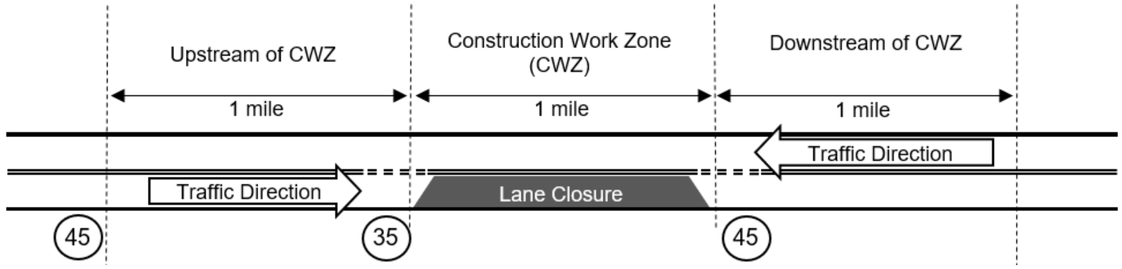
Figure 2.7: Lane configurations of partial lane closures at construction work zones on freeways and multi-lane highways.

2.6.2 One Full-Lane Closure on a Two-Lane Highway with Stop and Slow Signs or Pilot-Car Operation

When running the *MOVES* simulations for the two-lane highway scenarios, a three-mile segment was divided into three one-mile sections (shown in Figure 2.8): an upstream section, a middle section with the lane closure, and a downstream section. The middle section was considered the CWZ, and in this zone the parallel lane (the lane section next to the CWZ) was shared by vehicles alternating travel first in one direction and then the other under the control of either a crew with stop and slow signs or a pilot car. Two posted speed limits (55 mph and 45 mph) were assumed for two-lane highways.



(a) Two-lane highway (posted speed limit: 55 mph)



(b) Two-lane highway (posted speed limit: 45 mph)

Figure 2.8: Lane configurations of one full-lane closure at a construction work zone on a two-lane highway.

2.6.3 Summary of Scenarios

Table 2.4, Table 2.5, and Table 2.6 present three groups of scenarios based on freeway or highway type: freeway, multi-lane highway, and two-lane highway. The scenarios also consider CWZ operation type; traffic condition, including free-flow and congestion speeds, and pilot car operation; and average vehicle speed for the three sections in each closure (upstream, work zone, downstream).

Seven freeway scenarios (F-1 through F-7) were simulated for different congestion levels in a CWZ on a freeway system, shown in Table 2.4. The freeway's free-flow speeds were assumed to be between 55 mph and 75 mph.

Table 2.4: Scenario Descriptions for a CWZ on a Freeway

Scenario	Operation Type	Traffic Condition	Average Section Speed		
			Upstream	Work Zone	Downstream
F-1	No CWZ	Low free-flow speed	55	55	55
F-2	No CWZ	Free-flow speed	65	65	65
F-3	No CWZ	High free-flow speed	75	75	75
F-4	Lane closure in CWZ	No congestion	65	55	65
F-5	Lane closure in CWZ	Light congestion	45	55	65
F-6	Lane closure in CWZ	Medium congestion	25	55	65
F-7	Lane closure in CWZ	Heavy congestion	5	55	65

Eleven multi-lane highway scenarios (M-1 through M-11) are shown in Table 2.5. Three free-flow speeds were set for scenarios M-1 through M-3: 35, 45, and 55 mph. Scenarios M-4 through M-7 were for a lane closure in the CWZ where free-flow speed was 45 mph, and scenarios M-8 through M-11 were for the lane closure in the CWZ where the free-flow speed was 55 mph. The major difference between the freeway and multi-lane highway scenarios is their free-flow speeds.

Table 2.5: Scenario Descriptions for a CWZ on a Multi-Lane Highway

Scenario	Operation Type	Traffic Condition	Average Section Speed		
			Upstream	Work Zone	Downstream
M-1	No CWZ	Low free-flow speed	35	35	35
M-2	No CWZ	Free-flow speed	45	45	45
M-3	No CWZ	High free-flow speed	55	55	55
M-4	Lane closure in CWZ	No congestion	45	35	45
M-5	Lane closure in CWZ	Light congestion	35	35	45
M-6	Lane closure in CWZ	Medium congestion	15	35	45
M-7	Lane closure in CWZ	Heavy congestion	5	35	45
M-8	Lane closure in CWZ	No congestion	55	45	55
M-9	Lane closure in CWZ	Light congestion	35	45	55
M-10	Lane closure in CWZ	Medium congestion	15	45	55
M-11	Lane closure in CWZ	Heavy congestion	5	45	55

Two sets of two-lane highway scenarios (T-1 through T-4) are shown in Table 2.6. The drive cycles of the pilot car operation scenarios (T-2 and T-4) were developed from field observations, and the drive cycles for the vehicles following the pilot car were the same as those used for the pilot car's drive cycle at each free-flow speed (45 mph and 55 mph). The pilot car's CWZ round-trip travel times, which were set at 450 seconds for the 45 mph free-flow speed and 240 seconds for the 55 mph free-flow speed, defined the wait times for the vehicle drive cycles in scenarios T-2 and T-4, respectively.

Table 2.6: Scenario Descriptions for a CWZ on a Two-Lane Highway

Scenario	Operation Type	Traffic Condition	Average Section Speed (mph)		
			Upstream	Work Zone	Downstream
T-1	No lane closure	No congestion	45	45	45
T-2	Lane closure	Pilot-car operation	45	35	45
T-3	No lane closure	No congestion	55	55	55
T-4	Lane closure	Pilot-car operation	55	45	55

Figure 2.9 illustrates the drive cycles of vehicles traveling the three-mile segment following a pilot car in a two-lane road CWZ. The figure shows that vehicles decelerate and come to a stop at the end of the upstream section, where they idle until the pilot car returns to escort them through the CWZ. Then vehicles accelerate and follow the pilot car into the middle section of the CWZ and accelerate to free-flow speeds once they exit the CWZ's downstream section. Figure 2.10 shows the vehicle trajectory associated with these drive cycles. For simplicity, this simulation did not consider the random arrival times of vehicles to the closure. In reality, some vehicles may wait the entire time, others may arrive at various times while their direction is closed, and still others may arrive while their direction is open and be able to catch up to the queue to follow the pilot car through the closure. These details were not included because it was assumed they would not significantly change the simulation results. Similarly, the typical acceleration differences that occur after a pilot car control leaves—and vehicles exit the CWZ, with faster drivers executing maneuvers to pass slower ones—have not been considered.

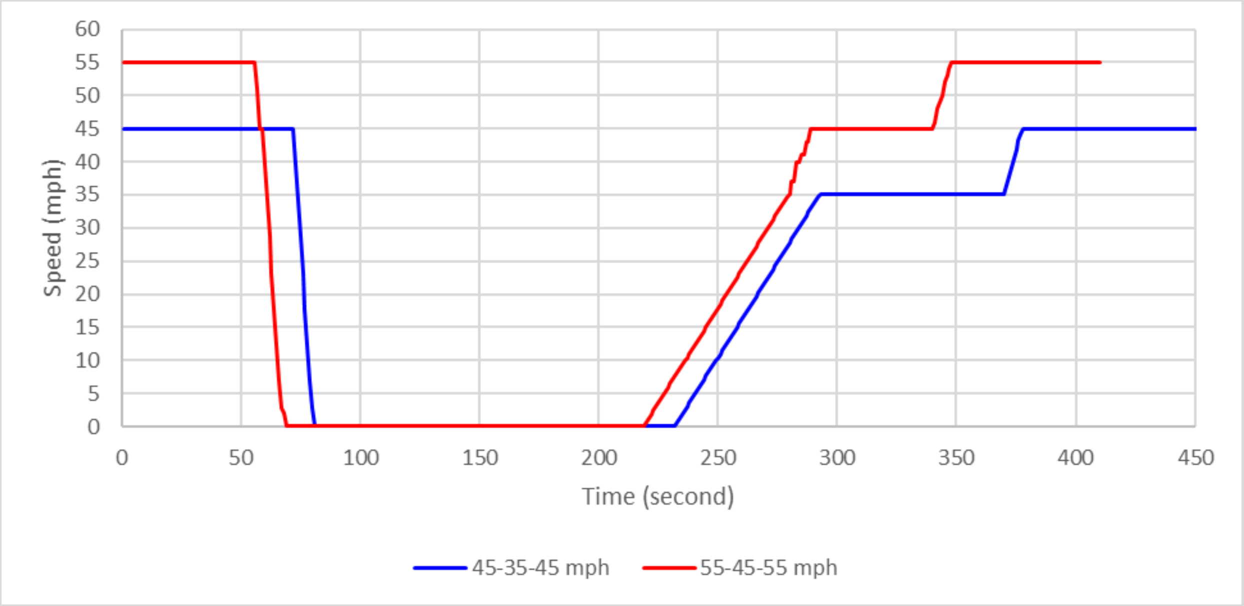


Figure 2.9: Drive cycles for pilot-car operation on a two-lane highway CWZ.

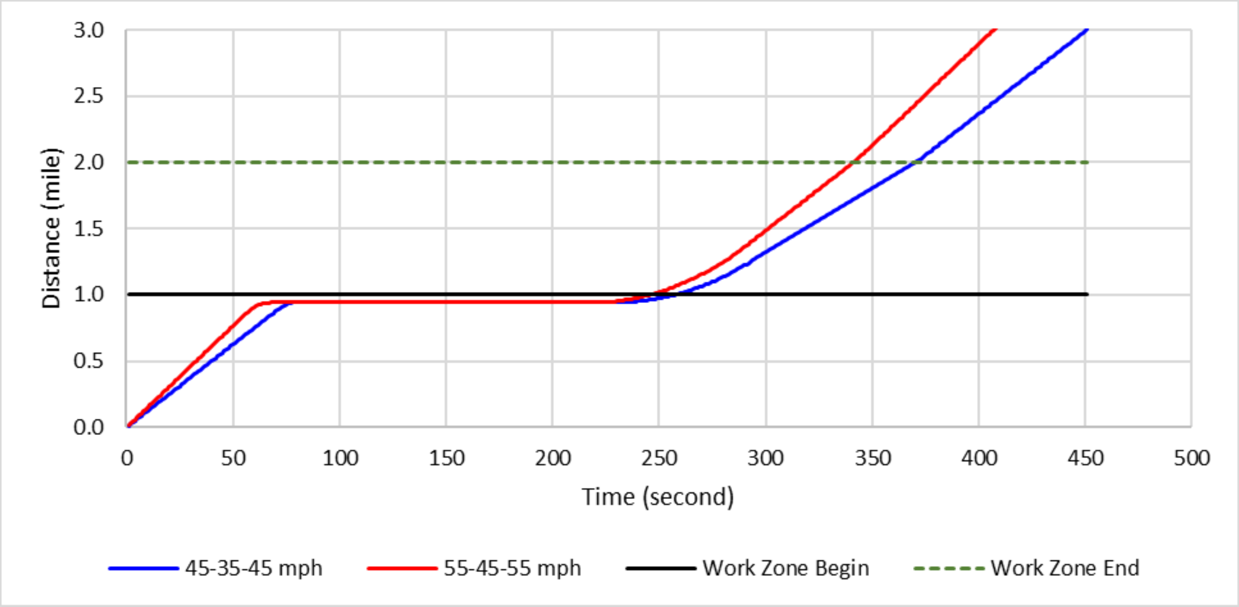


Figure 2.10: Vehicle trajectories for a pilot-car operation on a two-lane highway CWZ.

3 SIMULATION RESULTS

Since the aim of this study was to determine the effect of CWZ scenarios on the fuel economy of traffic, this technical memorandum has focused on the production and combustion of the fuels that are major emitters of air pollutants. The well-to-wheel (WTW) analysis discussed in this chapter presents a complete picture of the total life cycle impacts (of the airborne emissions discussed) that resulted from the different CWZ scenarios.

3.1 Freeway

3.1.1 Fuel Consumption and Environmental Impacts for Single-Vehicle Simulation

The simulation results for Scenarios F-1 through F-3, where there were no-CWZ operations and three different free-flow speeds, were used to compare the effects of free-flow speed on fuel consumption and pollutant emissions. The results shown in Table 3.1 reveal that three vehicle types—passenger cars (PC), sport utility vehicles (SUV), and light-duty trucks (LDT)—used in lower free-flow speed simulations generated fewer pollutant emissions and consumed less fuel. The results show that fuel consumption differences between free-flow speeds of 55 and 65 mph were virtually 0.2% for a PC (0.0973 gal./vehicle at 55 mph and 0.0975 gal./vehicle at 65 mph), 2.1% for an SUV (0.1318 gal./vehicle at 55 mph and 0.1346 gal./vehicle at 65 mph), and 1.1% for an LDT (0.1603 gal./vehicle at 55 mph and 0.1622 gal./vehicle at 65 mph) for a three-mile stretch. The results also show that fuel consumption differences between free-flow speeds of 65 mph and 75 mph were 8.7% for a PC (0.0975 gal./vehicle at 65 mph and 0.1061 gal./vehicle at 75 mph), 10.5% for an SUV (0.1346 gal./vehicle at 65 mph and 0.1488 gal./vehicle at 75 mph), and 7.6% for an LDT (0.1622 gal./vehicle at 65 mph and 0.1746 gal./vehicle at 75 mph) for a three-mile stretch. For heavy-duty trucks (HDT), the scenario with a 65 mph free-flow speed generated the least pollutant emissions and consumed the least fuel, and the scenario with a 55 mph free-flow speed generated the most pollutant emissions and consumed the most fuel. HDT fuel consumption at a 65 mph free-flow speed (0.1933 gal./vehicle) was 7.8% less than at a 55 mph free-flow speed (0.2085 gal./vehicle) and 6.4% less than at a 75 mph free-flow speed (0.2056 gal./vehicle) for a three-mile stretch.

In the table, the simulation results for Scenarios F-4 through F-7 show fuel consumption and pollutant emissions under four levels of traffic congestion (none, light, medium, and heavy) for a three-mile CWZ stretch. The results for fuel consumption and pollutant emissions from CWZ scenarios with no-congestion (F-4) were similar to those of the scenario with no-CWZ operation and a 65 mph free-flow speed (F-2), and the fuel consumption and pollutant emissions for the light congestion scenario (F-5) were slightly higher than for the CWZ scenarios with no congestion (F-4) for all vehicle types. The fuel consumption and pollutant emissions amounts for the scenarios with heavy congestion (F-7) were higher than in all the other scenarios. Specifically, in the heavy congestion, CWZ operation scenario, a PC consumed 86% more fuel, an SUV 76% more, an LDT 72% more, and an HDT 156% more than their counterparts in the no-CWZ, 65 mph free-flow speed scenario (Table 3.2).

Table 3.1: Pollutant Emissions Rates and Fuel Consumption Results for All the Vehicle Types Under the No-CWZ and CWZ Operations on a Freeway

Vehicle Class	Scenario[a]	Average Section Speed (mph)			Pollutant Emission Rate (g/3 mi. CWZ stretch)				Fuel Consumption[b] (gal./3 mi. CWZ stretch)	Fuel Economy (mi./gal.)
		Upstream	Work Zone	Downstream	CO_2-e	NO_x	SO_2	$PM_{2.5}$		
Passenger car (PC)	F-1	55	55	55	1,105	1.1173	0.3347	0.0517	0.0973	30.819
	F-2	65	65	65	1,107	1.1630	0.3353	0.0503	0.0975	30.765
	F-3	75	75	75	1,204	1.3527	0.3647	0.0550	0.1061	28.284
	F-4	65	55	65	1,106	1.1478	0.3351	0.0508	0.0975	30.783
	F-5	45	55	65	1,118	1.1316	0.3388	0.0530	0.0985	30.447
	F-6	25	55	65	1,222	1.2160	0.3703	0.0624	0.1077	27.857
	F-7	5	55	65	2,058	1.7042	0.6235	0.1100	0.1813	16.543
Sport utility vehicle (SUV)	F-1	55	55	55	1,496	1.9169	0.4533	0.0672	0.1318	22.758
	F-2	65	65	65	1,528	2.0645	0.4628	0.0674	0.1346	22.289
	F-3	75	75	75	1,689	2.4898	0.5116	0.0757	0.1488	20.164
	F-4	65	55	65	1,517	2.0153	0.4596	0.0673	0.1337	22.443
	F-5	45	55	65	1,519	1.9522	0.4603	0.0691	0.1339	22.411
	F-6	25	55	65	1,645	2.0381	0.4983	0.0800	0.1449	20.701
	F-7	5	55	65	2,689	2.6640	0.8148	0.1335	0.2370	12.661
Light-duty truck (LDT)	F-1	55	55	55	1,947	4.4977	0.4885	0.2222	0.1603	18.712
	F-2	65	65	65	1,970	4.5371	0.4941	0.2186	0.1622	18.500
	F-3	75	75	75	2,120	5.0664	0.5319	0.2194	0.1746	17.186
	F-4	65	55	65	1,962	4.5239	0.4922	0.2198	0.1616	18.570
	F-5	45	55	65	1,975	4.5825	0.4954	0.2257	0.1626	18.452
	F-6	25	55	65	2,164	5.2395	0.5428	0.2610	0.1781	16.840
	F-7	5	55	65	3,388	9.5720	0.8496	0.5349	0.2788	10.759
Heavy-duty truck (HDT)	F-1	55	55	55	2,534	8.8979	0.6353	0.4191	0.2085	14.388
	F-2	65	65	65	2,349	8.2528	0.5891	0.3732	0.1933	15.516
	F-3	75	75	75	2,498	8.7895	0.6265	0.3554	0.2056	14.589
	F-4	65	55	65	2,411	8.4678	0.6045	0.3885	0.1984	15.121
	F-5	45	55	65	2,621	9.2095	0.6573	0.4236	0.2157	13.906
	F-6	25	55	65	3,089	10.9209	0.7746	0.5042	0.2543	11.799
	F-7	5	55	65	6,005	22.4755	1.5052	1.1320	0.4940	6.072

[a] The scenarios from F1 to F7 are described in Table 2.4.

[b] PCs and SUVs are gasoline-fueled vehicles and LDTs and HDTs are diesel-fueled vehicles.

Figure 3.1 shows fuel consumption per vehicle type under the different operation types and congestion levels for traveling a three-mile stretch. Improving the congestion level from heavy (average speed 5 mph) to medium (average speed 25 mph) resulted in a 41% fuel savings for a PC, 39% for an SUV, 36% for an LDT, and 49% for an HDT on a freeway with a CWZ.

Table 3.2: Fuel Consumption and Percent Changes for a Single Vehicle for CWZ and No-CWZ Scenarios with 65 mph Speed for Freeway

Vehicle Type	Fuel Consumption[1] for the Baseline Scenario (gal./3 mi. stretch)	Excess Fuel Consumption[a] for CWZ Scenarios (gal./3 mi. stretch) (% change)			
	No-CWZ, No Congestion (65-65-65 mph)	No Congestion (65-55-65 mph)	Light Congestion (45-55-65 mph)	Medium Congestion (25-55-65 mph)	Heavy Congestion (5-55-65 mph)
Passenger car (PC)	0.0975	-0.0001 (-0.1%)	0.0010 (1.0%)	0.0102 (10.4%)	0.0838 (86.0%)
Sport utility vehicle (SUV)	0.1346	-0.0009 (-0.7%)	-0.0007 (-0.5%)	0.0103 (7.7%)	0.1024 (76.1%)
Light-duty truck (LDT)	0.1622	-0.0006 (-0.4%)	0.0004 (0.3%)	0.0160 (9.9%)	0.1167 (72.0%)
Heavy-duty truck (HDT)	0.1933	0.0051 (2.6%)	0.0224 (11.6%)	0.0609 (31.5%)	0.3007 (155.5%)

[a] PCs and SUVs are gasoline-fueled vehicles, and LDTs and HDTs are diesel-fueled vehicles.

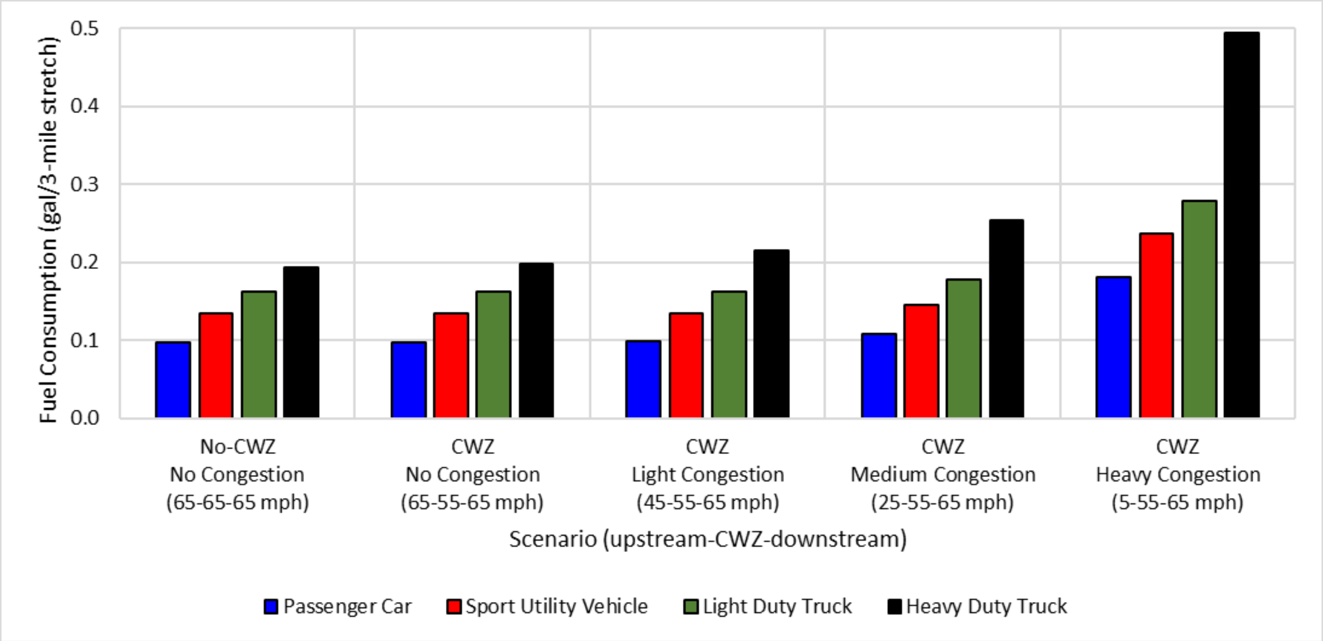


Figure 3.1: Comparison of fuel consumption for operation type and congestion level scenarios—freeway.

3.1.2 Fuel Consumption and Environmental Impacts Based on Hourly Traffic Aggregation Data

To obtain fuel consumption estimates more reflective of real traffic conditions, the single-vehicle scenario simulation results were aggregated using the actual hourly traffic volumes of each vehicle type recorded on a specific freeway segment (Sacramento County, Interstate 80 eastbound, Post Mile 97.9). In the hour between 7:00 a.m. to 8:00 a.m., 5,374 vehicles traveled through the CWZ and 5% of the vehicles were trucks. Based on the data for the segment, the PC/SUV ratio was assumed to be 60/40 and the LDT/HDT ratio was assumed to be 30/70 for trucks *(28).*

As shown in Table 3.3, in this scenario, 49.5 gal. of diesel and 573.5 gal. of gasoline were consumed in the *no-CWZ, no-congestion* operation and 50.4 gal. of diesel and 571.5 gal. of gasoline were consumed in the *CWZ, no-congestion* operation. Due to the reduced speed limit (from 65 mph to 55 mph) in the CWZ segment, total gasoline consumption decreased by just 0.4%. However, in this CWZ scenario total diesel consumption increased by 1.8%.

The total consumption of diesel (115.5 gal.) and gasoline (1,039.3 gal.) under heavy congestion were 133% and 81% greater, respectively, than under the no-CWZ, no congestion operation scenario (49.5 gal. of diesel and 573.4 gal. of gasoline) and 86% and 66% greater, respectively, than under the *CWZ*, medium congestion operation scenario (62.2 gal. of diesel and 625.8 gal. of gasoline). These results indicate that in these freeway CWZ scenarios, improving the traffic congestion level from heavy (average speed 5 mph) to medium (average speed 25 mph) reduced fuel consumption by 40%.

When the results from the CWZ heavy congestion scenario (F-7) are compared to the results of the no-CWZ operation scenario (F-2) without congestion and a 65 mph free-flow speed, CO_2-e increased by 86%, SO_2 increased by 85%, NO_x increased by 62%, and $PM_{2.5}$ increased by 128%.

Table 3.3: Pollutant and Fuel Consumption for Multiple Vehicles on Freeway

Environmental Impacts[a]	Scenarios									
	No-CWZ No Congestion (65-65-65 mph)		CWZ No Congestion (65-55-65 mph)		CWZ Light Congestion (45-55-65 mph)		CWZ Medium Congestion (25-55-65 mph)		CWZ Heavy Congestion (5-55-65 mph)	
	Quantity	Change	Quantity	Change (%)	Quantity	Change (%)	Quantity	Change (%)	Quantity	Change (%)
CO_2-e (kg/3 mi.)	7,112	Baseline	7,098	-0.2	7,179	0.9	7,858	10.5	13,198	85.6
NO_x (kg/3 mi.)	9.697	Baseline	9.589	-1.1	9.555	-1.5	10.364	6.9	15.661	61.5
SO_2 (kg/3 mi.)	2.123	Baseline	2.118	-0.2	2.141	0.9	2.341	10.3	3.925	84.9
$PM_{2.5}$ (kg/3 mi.)	0.380	Baseline	0.384	1.1	0.401	5.7	0.470	23.9	0.866	128.1
Diesel Consumption (gal./3 mi.)	49.5	Baseline	50.4	1.8	53.7	8.6	62.2	25.8	115.5	133.3
Gasoline Consumption (gal./3 mi.)	573.5	Baseline	571.5	-0.4	575.2	0.3	625.8	9.1	1,039.3	81.2

[a] Of a total of 5,374 vehicles, 56% were Gas-PC, 38% were Gas-SUV, 2% were Diesel-LDT, and 4% were Diesel-HDT.

3.2 Multi-Lane Highway

3.2.1 Fuel Consumption and Environmental Impacts for Single-Vehicle Simulation

Table 3.4 (gasoline for PC and SUV) and Table 3.5 (diesel for LDT and HDT) show the results of scenarios M-1 to M-3 fuel consumption and pollutant emissions rates for three levels of free-flow speed in the no-CWZ operation set up. These results were used to compare the changes between the scenarios. The results show that vehicles traveling at the highest free-flow speed, 55 mph, consumed less fuel than in the 45 mph and 35 mph free-flow speed scenarios. In the 55 mph free-flow speed scenario, the PC, SUV, LDT, and HDT consumed, respectively, 10%, 8%, 10%, and 28% less fuel than in the 35 mph free-flow speed scenario. The CO_2-e changes showed similar trends as the fuel consumption changed for all the vehicle types, and the amount of SO_2 and $PM_{2.5}$ decreased by between 8% to 28% for all the vehicle types with a change of free-flow speed from 35 mph (M-1) to 55 mph (M-3). Changing the free-flow speed from 35 mph (M-1) to 55 mph (M-3) decreased the amount of NO_x emissions from the PC, LDT, and HDT by 5%, 16%, and 29%, respectively, but increased those emissions from the SUV by 1%. The differences in fuel consumption and NO_x emissions between 35 mph and 55 mph were much higher for the SUV.

The simulation results for scenarios M-4 through M-11 (with CWZ), shown in Table 3.4 and Table 3.5, indicate that the fuel consumption and pollutant emissions amounts for the no-congestion scenario (M-8) for all vehicle types were similar to the results for the no-CWZ, 45 mph free-flow speed scenario (M-3), and that the results of the light congestion scenario (M-9) were slightly higher than for the no-congestion scenarios (M-8). The fuel consumption and pollutant emissions rates of the scenarios with heavy congestion (M-7) were higher than those of all the other scenarios for all vehicle types. Compared with the no-CWZ operation scenario in Table 3.6, in a CWZ, heavy congestion operation fuel consumption increased by 87% for the PC, 80% for the SUV, 75% for the LDT, and 145% for the HDT.

Figure 3.2 shows fuel consumption per vehicle type under the different operation types and congestion levels. In scenarios with a CWZ on a multi-lane highway, changing the congestion level from heavy (average speed 5 mph) to medium (average speed 15 mph) resulted in fuel savings of 33% for the PC, 32% for the SUV, 30% for the LDT, and 39% for the HDT. The results shown in this section indicate that the potential fuel savings that result from improving the traffic congestion level in a freeway CWZ from heavy to medium could surpass those resulting from making a similar change on a multi-lane highway (Section 3.1).

Table 3.4: Pollutant Emissions Rates and Fuel Consumption of the Passenger Car and the Sport Utility Vehicle for the Multi-Lane Highway Work Zone Scenarios

Vehicle Class	Scenario[a]	Average Section Speed (mph)			Pollutant Emission Rate (g/3 mi. stretch)				Gasoline Consumption (gal./3 mi. stretch)	Fuel Economy (mi./gal.)
		Upstream	Work Zone	Downstream	CO_2-e	NO_x	SO_2	$PM_{2.5}$		
Passenger car (PC)	M-1	35	35	35	1,226	1.1704	0.3715	0.0664	0.1081	27.763
	M-2	45	45	45	1,143	1.1146	0.3464	0.0569	0.1007	29.778
	M-3	55	55	55	1,105	1.1173	0.3347	0.0517	0.0973	30.819
	M-4	45	35	45	1,171	1.1332	0.3548	0.0601	0.1032	29.075
	M-5	35	35	45	1,199	1.1518	0.3632	0.0632	0.1056	28.404
	M-6	15	35	45	1,425	1.3108	0.4316	0.0789	0.1255	23.900
	M-7	5	35	45	2,111	1.7058	0.6395	0.1171	0.1860	16.130
	M-8	55	45	55	1,118	1.1164	0.3386	0.0534	0.0985	30.464
	M-9	35	45	55	1,158	1.1341	0.3509	0.0583	0.1020	29.398
	M-10	15	45	55	1,384	1.2931	0.4193	0.0740	0.1219	24.600
	M-11	5	45	55	2,070	1.6881	0.6272	0.1122	0.1824	16.445
Sport utility vehicle (SUV)	M-1	35	35	35	1,621	1.8919	0.4910	0.0831	0.1428	21.008
	M-2	45	45	45	1,534	1.8752	0.4648	0.0727	0.1352	22.193
	M-3	55	55	55	1,496	1.9169	0.4533	0.0672	0.1318	22.758
	M-4	45	35	45	1,563	1.8808	0.4735	0.0762	0.1377	21.783
	M-5	35	35	45	1,592	1.8863	0.4823	0.0796	0.1403	21.388
	M-6	15	35	45	1,872	2.0830	0.5671	0.0977	0.1649	18.189
	M-7	5	35	45	2,733	2.5926	0.8280	0.1406	0.2408	12.458
	M-8	55	45	55	1,509	1.9030	0.4571	0.0690	0.1329	22.566
	M-9	35	45	55	1,550	1.8947	0.4697	0.0743	0.1366	21.962
	M-10	15	45	55	1,830	2.0913	0.5545	0.0924	0.1613	18.602
	M-11	5	45	55	2,691	2.6009	0.8154	0.1353	0.2372	12.650

[a] The scenarios (M1 to M11) are described in Table 2.5.

Table 3.5: Pollutant Emissions Rates and Fuel Consumption of the Light-Duty Truck and the Heavy-Duty Truck for the Multi-Lane Highway CWZ Scenarios

Vehicle Class	Scenario[a]	Average Section Speed (mph)			Pollutant Emission Rate (g/3 mi. stretch)				Diesel Consumption (gal./3 mi. stretch)	Fuel Economy (mi./gal.)
		Upstream	Work Zone	Downstream	CO_2-e	NO_x	SO_2	$PM_{2.5}$		
Light-duty truck (LDT)	M-1	35	35	35	2,156	5.3494	0.5407	0.2639	0.1775	16.905
	M-2	45	45	45	2,007	4.7126	0.5035	0.2363	0.1653	18.153
	M-3	55	55	55	1,947	4.4977	0.4885	0.2222	0.1603	18.712
	M-4	45	35	45	2,057	4.9249	0.5159	0.2455	0.1693	17.717
	M-5	35	35	45	2,106	5.1371	0.5283	0.2547	0.1734	17.301
	M-6	15	35	45	2,466	6.3906	0.6184	0.3324	0.2030	14.782
	M-7	5	35	45	3,470	9.9144	0.8702	0.5546	0.2856	10.504
	M-8	55	45	55	1,967	4.5693	0.4935	0.2269	0.1620	18.522
	M-9	35	45	55	2,037	4.8532	0.5109	0.2408	0.1677	17.891
	M-10	15	45	55	2,396	6.1067	0.6010	0.3185	0.1972	15.210
	M-11	5	45	55	3,400	9.6305	0.8528	0.5407	0.2799	10.719
Heavy-duty truck (HDT)	M-1	35	35	35	3,517	12.4534	0.8818	0.5713	0.2894	10.365
	M-2	45	45	45	2,981	10.4780	0.7474	0.4786	0.2453	12.229
	M-3	55	55	55	2,534	8.8979	0.6353	0.4191	0.2085	14.388
	M-4	45	35	45	3,160	11.1364	0.7922	0.5095	0.2600	11.537
	M-5	35	35	45	3,338	11.7949	0.8370	0.5404	0.2747	10.920
	M-6	15	35	45	4,120	14.8522	1.0329	0.6978	0.3390	8.849
	M-7	5	35	45	6,543	24.4024	1.6401	1.2179	0.5383	5.573
	M-8	55	45	55	2,683	9.4246	0.6727	0.4390	0.2208	13.588
	M-9	35	45	55	3,010	10.6097	0.7548	0.4897	0.2478	12.109
	M-10	15	45	55	3,792	13.6670	0.9507	0.6471	0.3120	9.614
	M-11	5	45	55	6,215	23.2173	1.5580	1.1672	0.5114	5.867

[a] The scenarios (M1 to M11) are described in Table 2.5.

Table 3.6: Fuel Consumption Changes for a Single Vehicle on CWZ for Multi-Lane Highway for CWZ Scenarios

Vehicle Type	Fuel Consumption[1] for the Baseline Scenario (gal./3 mi. stretch)	Excess Fuel Consumption[1] for CWZ Scenarios (gal./3 mi. stretch) (% change)			
	No-CWZ, No Congestion (55-55-55 mph)	No Congestion (55-45-55 mph)	Light Congestion (35-45-55 mph)	Medium Congestion (15-45-55 mph)	Heavy Congestion (5-45-55 mph)
Passenger car (PC)	0.0973	0.0011 (1.2%)	0.0047 (4.8%)	0.0246 (25.3%)	0.0851 (87.4%)
Sport utility vehicle (SUV)	0.1318	0.0011 (0.8%)	0.0048 (3.6%)	0.0295 (22.3%)	0.1053 (79.9%)
Light-duty truck (LDT)	0.1603	0.0016 (1.0%)	0.0074 (4.6%)	0.0369 (23.0%)	0.1196 (74.6%)
Heavy-duty truck (HDT)	0.2085	0.0123 (5.9%)	0.0392 (18.8%)	0.1035 (49.6%)	0.3028 (145.2%)

[1] PCs and SUVs are gasoline-fueled vehicles and LDTs and HDTs are diesel-fueled vehicles.

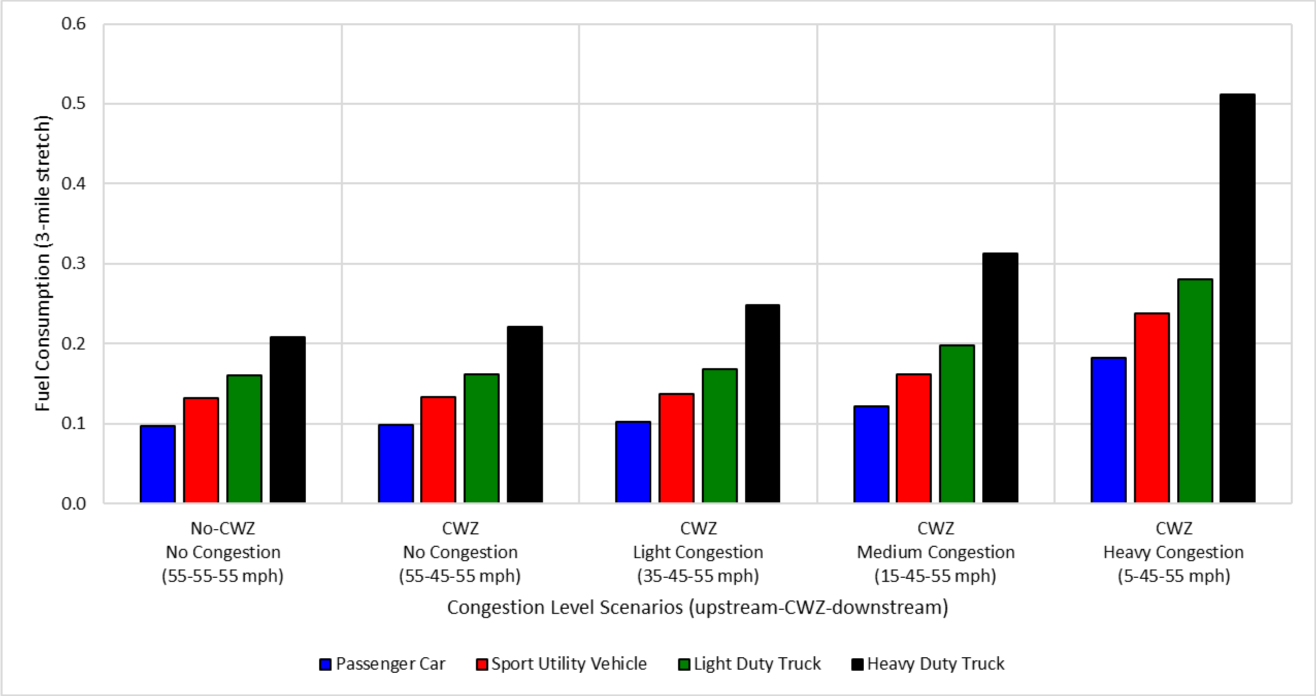


Figure 3.2: Comparison of fuel consumption for operation type and congestion level scenarios—multi-lane highway.

3.2.2 Fuel Consumption and Environmental Impacts Based on Aggregated Hourly Traffic Data

To better reflect real traffic conditions in fuel consumption estimates, the single-vehicle scenario simulation results were aggregated real hourly traffic volumes of each vehicle type observed on a specific multi-lane city boulevard (westbound College Town Drive in Sacramento). In the demonstration simulation, an hourly traffic volume of 1,000 vehicles—with 10% heavy vehicles—traveled through a CWZ on a multi-lane boulevard for one hour (from

7:00 a.m. to 8:00 a.m.). The PC/SUV ratio was assumed to be 60/40 and the LDT/HDT ratio was assumed to be 60/40 based on the data for the selected segment.

As shown in Table 3.7, the 1,000 vehicles traveling the three-mile segment of multi-lane road for one hour consumed 18.0 gal. of diesel and 100.0 gal. of gasoline in the no-CWZ operation without traffic congestion scenario and 18.5 gal. of diesel and 101.0 gal. of gasoline in the CWZ operation without traffic congestion scenario. Due to the lower speed limit (from 55 mph to 45 mph) in the CWZ segment, total diesel and total gasoline consumption in the CWZ without traffic congestion scenario were higher, by 3.3% and 1.0%, respectively.

The diesel and gasoline consumption in a CWZ under heavy congestion (37.2 gal. of diesel and 183.9 gal. of gasoline) were 107% and 84% greater, respectively, than the diesel and gasoline consumption under the no-CWZ, no-congestion scenario (18.0 gal. of diesel and 100.0 gal. of gasoline) and 53% and 48% greater, respectively, than the diesel and gasoline consumption under the CWZ-medium congestion scenario (24.3 gal. of diesel and 123.9 gal. of gasoline). This result indicates that improving the traffic congestion level from heavy congestion (average speed 5 mph) to medium congestion in the CWZ (average speed 15 mph) would yield a 33% fuel savings (from 37.2 gal. to 24.3 gal. of diesel and from 183.9 gal. to 123.9 gal. of gasoline). A further improvement from heavy congestion to no congestion in the CWZ would yield a savings of 50% of total diesel and 45% of total gasoline (from 37.2 gal. to 18.5 gal. of diesel and from 183.9 gal. to 101.0 gal. of gasoline) for a multi-lane highway CWZ.

Under the CWZ, heavy congestion scenario, all the pollutant emission parameters also increased dramatically. CO_2-e increased by 88%, NO_x by 75% SO_2 by 87%, and $PM_{2.5}$ 129% under this scenario (M-11) compared to the results of the no-CWZ, no-congestion scenario (M-3).

Table 3.7: Pollutant Emissions and Fuel Consumption for Multiple Vehicles on a Multi-Lane Highway

Environmental Impacts[a]	Scenarios									
	No CWZ No Congestion (55-55-55 mph)		CWZ No Congestion (55-45-55 mph)		CWZ Light Congestion (35-45-55 mph)		CWZ Medium Congestion (15-45-55 mph)		CWZ Heavy Congestion (5-45-55 mph)	
	Quantity	Change	Quantity	Change (%)	Quantity	Change (%)	Quantity	Change (%)	Quantity	Change (%)
CO_2-e (kg/3 mi.)	1,353	Baseline	1,372	1.4	1,426	5.4	1,702	25.7%	2,539	87.7
NO_x (kg/3 mi.)	1.919	Baseline	1.939	1.0	2.010	4.7	2.364	23.2%	3.354	74.8
SO_2 (kg/3 mi.)	0.399	Baseline	0.404	1.3	0.419	5.2	0.500	25.5%	0.746	87.1
$PM_{2.5}$ (kg/3 mi.)	0.082	Baseline	0.085	3.3	0.092	12.3	0.118	43.9%	0.188	129.2
Diesel Consumption (gal./3 mi.)	18.0	Baseline	18.5	3.3	20.0	11.2	24.3	35.4%	37.2	107.4
Gasoline Consumption (gal./3 mi.)	100.0	Baseline	101.0	1.0	104.3	4.3	123.9	23.9%	183.9	83.8

[a] Of a total of 1,000 vehicles, 54% were Gas-PC, 36% were Gas-SUV, 6% were Diesel-LDT, and 4% were Diesel-HDT.

3.3 Two-Lane Highway with Pilot-Car Operation

3.3.1 Fuel Consumption and Environmental Impacts of a Single Vehicle

MOVES simulations were used to generate results for fuel consumption and pollutant emissions per vehicle type under the no-CWZ and the pilot-car operation scenarios for a one-lane closure in a CWZ on a two-lane highway with a 55 mph posted speed limit, shown in Table 3.8. Two scenarios, the no-CWZ and the pilot-car operation on a CWZ, were considered for this comparison of fuel consumption and pollutant emissions. The results show that the fuel consumption of the PC in the pilot-car operation was 13% higher than for the no-CWZ operation scenario. Specifically, the PC consumed 0.1007 gal. in the no-CWZ scenario and 0.1137 gal. in the pilot-car operation scenario. Similarly, the fuel consumption of an SUV for the pilot-car operation was 11% higher than for the no-CWZ operation. In this case, the SUV consumed 0.1352 gal. for the no-CWZ operation and 0.1496 gal. for the pilot-car operation. For the LDT and HDT, fuel consumption results for the pilot-car operation scenario were 6% and 19% higher, respectively, than for the no-CWZ operation scenarios.

The HDT vehicle type showed the greatest negative influence in pollutant emissions under the pilot-car operation scenario. NO_x increased by 24% and $PM_{2.5}$ increased by 91% under the CWZ with a pilot-car scenario, compared to the no-congestion, no-CWZ scenario. However, the difference between the no-CWZ operation scenario and the pilot-car scenario was not as large as the differences under the CWZ heavy congestion scenarios for freeways and multi-lane highways.

Table 3.8: Pollutant Emissions and Fuel Consumption Changes for a Single Vehicle with No-CWZ or Pilot-Car Operation in Two-Lane Highway Scenarios

Vehicle Types	Pollutant Emissions (g)								Fuel Consumption[a] (gal.)	
	CO_2-e		NO_x		SO_2		$PM_{2.5}$			
	No CWZ	Pilot Car	No CWZ	Pilot Car	No CWZ	Pilot Car	No CWZ	Pilot Car	No CWZ	Pilot Car
	Difference		Difference		Difference		Difference		Difference	
Passenger cars (PC)	1,143	1,290	1.1146	1.1579	0.3464	0.3909	0.0569	0.0603	0.1007	0.1137
	13%		4%		13%		6%		13%	
Sport utility vehicles (SUV)	1,534	1,698	1.8752	1.8808	0.4648	0.5144	0.0727	0.0746	0.1352	0.1496
	11%		0%		11%		3%		11%	
Light-duty trucks (LDT)	2,007	2,137	4.7126	5.8564	0.5035	0.5361	0.2363	0.3202	0.1653	0.1759
	6%		24%		6%		36%		6%	
Heavy-duty trucks (HDT)	2,981	3,558	10.4780	13.0199	0.7474	0.8921	0.4786	0.9136	0.2453	0.2928
	19%		24%		19%		91%		19%	

[a] PCs and SUVs are gasoline-fueled vehicles and LDTs and HDTs are diesel-fueled vehicles.

3.3.2 Fuel Consumption and Environmental Impacts for Hourly Traffic Aggregation

The hourly traffic counts on a two-lane highway segment (State Route 12, Sacramento County, Post Mile 5.63) were used to estimate fuel consumption and pollutant emissions changes for a pilot-car operation on a two-lane highway CWZ compared to a no-CWZ setup. The hourly traffic volume—260 vehicles with 15% heavy vehicles—traveled in the CWZ on the two-lane highway for one hour (from 7:00 a.m. to 8:00 a.m.). The PC/SUV ratio was assumed to be 60/40 and the LDT/HDT ratio was assumed to be 35/65 based on the data for the selected segment.

The 260 vehicles traveling the three-mile segment for one hour consumed 9.78 gal. of diesel and 28.29 gal. of gasoline in the CWZ with pilot-car operation scenario, 15% more diesel and 12% more gasoline than the 8.45 gallons of diesel and 25.29 gallons of gasoline consumed in the no-congestion, no-CWZ operation scenario, shown in Table 3.9. The HDT showed the largest difference in fuel consumption between the no-CWZ, no-congestion and CWZ with pilot-car operation scenarios, consuming 19% more diesel in the CWZ with pilot-car operation scenario.

The LDT and HDT both showed increases in all the pollutant emission parameters in the pilot-car scenarios. Comparing the results from these vehicles in the CWZ with pilot-car scenario against the results generated in the no-congestion, no-CWZ scenario—both on a two-lane highway—showed that LDT emissions of CO_2-e increased by 6%, NO_x by 27%, SO_2 by 6%, and $PM_{2.5}$ by 44% and that HDT emissions of CO_2-e increased by 19%, NO_x by 25%, SO_2 by 19%, and $PM_{2.5}$ by 106%. A comparison of these two scenarios for the PC and the SUV showed that NO_x decreased by 4% for the PC and 6% for the SUV, and $PM_{2.5}$ decreased by 7% for the PC and 15% for the SUV. For aggregated traffic for one hour, CO_2-e increased by 13%, NO_x by 14%, SO_2 by 13%, and $PM_{2.5}$ by 65% for the CWZ with pilot-car operation scenario.

The fuel consumption and pollutant emissions changes observed between the no-congestion, no-CWZ operation scenario and the CWZ with pilot-car operation scenario were smaller than the changes observed in the freeway and multi-lane highway CWZ scenarios. Improving the pilot-car operation method and/or selecting different lane closure hours could yield fuel consumption savings and reduce pollutant emissions if those scenarios were optimized to avoid making heavy trucks slow, stop, and accelerate.

Table 3.9: Pollutant Emission and Fuel Consumption Changes for Multiple Vehicles in the No-CWZ and CWZ with Pilot-Car Operation for Two-Lane Highway Scenarios

Vehicle Types (Numbers)	**Pollutant Emissions (kg)**								**Diesel Consumption[a] (gal.)**		**Gasoline Consumption[a] (gal.)**	
	CO$_2$-e		**NO$_x$**		**SO$_2$**		**PM$_{2.5}$**					
	No CWZ	**Pilot Car**	**No CWZ**	**Pilot Car**	**No CWZ**	**Pilot Car**	**No CWZ**	**Pilot Car**	**No CWZ**	**Pilot Car**	**No CWZ**	**Pilot Car**
	Difference		**Difference**		**Difference**		**Difference**		**Difference**		**Difference**	
Passenger cars (PC) (133)	152	172	77	74	0.76	0.85	2.61	2.42	—	—	13.40	15.12
	13%		-4%		13%		-7%		—		13%	
Sport utility vehicles (SUV) (88)	135	149	102	96	0.67	0.74	2.00	1.69	—	—	11.98	13.26
	11%		-6%		11%		-15%		—		11%	
Light-duty trucks (LDT) (14)	28	30	54	69	0.21	0.22	2.53	3.66	2.31	2.46	—	—
	6%		28%		6%		44%		6%		—	
Heavy-duty trucks (HDT) (25)	75	89	229	286	0.55	0.66	9.91	20.38	6.13	7.32	—	—
	19%		25%		19%		106%		19%		—	
Total (260)	390	440	462	525	2.19	2.48	17.05	28.16	8.45	9.78	25.29	28.29
	13%		14%		13%		65%		16%		12%	

[a] Of a total of 260 vehicles, 51% were Gas-PC, 34% were Gas-SUV, 5% were Diesel-LDT, were 10% Diesel-HDT.

4 APPLYING THE RESULTS

Lane closures are often inevitable when pavement M&R treatments are being applied to the highway system. These closures can reduce traffic capacity, which may already exceed demand, and cause traffic delays on most urban highways during peak hours—and even during off-peak hours if the closures sufficiently reduce capacity. This study provided a framework for analyzing CWZs and demonstrated the use of the framework in a few select cases. The study also provided quantitative results for CWZ lane closures with different types of roadway facilities, operational approaches, and traffic conditions. CWZs with heavy traffic congestion produce stop-and-go conditions that consume much more fuel and produce greater amounts of pollutant emissions, regardless of closure type and vehicle type. In addition, as construction durations lengthen, fuel consumption and pollutant emissions increase. These situations become more extreme if the construction activity is carried out during peak traffic hours.

This framework can be used to quantify the environmental impacts for construction duration (schedule), frequency, and timing for pavement treatment alternatives and can be used to reduce excessive fuel consumption and pollutant emissions.

The following are next steps for this project:

- Develop a larger factorial of CWZ schedules and types on different types of lane configurations and demand/capacity levels.
- Develop regression equations, neural networks, or other methods to rapidly find results from the factorial that can be used for LCA in pavement management, conceptual project evaluation, and project design software used by Caltrans.
- Use the results of the factorial to make recommendations for the optimal design of CWZ lane closure strategies, if the results suggest that changes in emissions and fuel use are warranted for any estimated cost changes.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A framework was developed for modeling changes in fuel use and air pollutant emissions for CWZ closures in a life cycle approach (well-to-wheel). The framework was then demonstrated using realistic traffic conditions, drive cycles, and CWZ operation scenarios in the *MOVES* simulation model. The simulations used the framework for three examples of CWZ operations under different traffic congestion levels (light, medium, and heavy congestion) on freeways, multi-lane highways, and two-lane highways.

The fuel consumption and pollutant emissions from the CWZ scenario were compared with those from the no-congestion, no-CWZ operation scenario. Lessening the traffic congestion upstream of the CWZ from heavy (average speed of 5 mph) to medium (average speed 15 to 25 mph) reduced fuel consumption by approximately 40% on the freeway and 32% on the multi-lane road. This change also reduced pollutant emissions. It was found in all the scenarios that limiting start-and-stop conditions for heavy trucks was particularly important for improving overall fuel use and lowering air pollutant emissions relative to free-flow conditions.

Evaluation of the CWZ with a pilot-car operation on two-lane highways indicated that these closures may increase fuel consumption by approximately 10% and generate between 10% and 56% more air pollutant emissions depending on vehicle type.

The next steps for this research will be to analyze a larger factorial of cases and to use those results to include CWZs in LCA calculations in Caltrans pavement management, concept evaluation, and project design scenarios.

5.2 Recommendations

The results for the various scenarios indicate that CWZs have a more pronounced effect on pollutant emissions from heavy-duty vehicles than from smaller vehicles. Therefore, development of CWZs that limit the effects on heavy trucks will help mitigate fuel consumption and pollutant emissions increases from construction closures.

The simulation results described in this technical memorandum could be considered in quantifying the environmental impact of CWZs in the LCA framework for pavement management, concept evaluation, and project design. The results could also be used in studies to evaluate pavement design lives (20 years versus 40 years) with future M&R schedules in life cycle cost analysis (LCCA) and environmental LCA, in selecting appropriate pavement types for truck lanes and in-place recycling, and in evaluating lane closure schedules and tactics to minimize impacts from CWZs on highways for project-specific traffic congestion levels.

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APPENDIX A: MOVES INPUT SUMMARY

Table A.1: General Input Information for MOVES

Input Variable	Value
Month ID	5
Zone ID	60670 (Sacramento)
Hour ID	8
Temperature	70 °F
Relative humidity	50%
Hour name	Hour beginning at 7:00 a.m.

Table A.2: Operation Mode Input in MOVES (a)

Begin Model Year ID	End Model Year	Operation Mode ID	Operation Mode Fraction
1960	2050	200	0.5
1960	2050	201	0.5
1960	2050	203	0
1960	2050	204	0

Table A.3: Operation Mode Input in MOVES (b)

Operation Mode ID	Operation Mode Name
200	Extended Idling
201	Hoteling Diesel Aux
203	Hoteling Battery AC
204	Hoteling Auxiliary Power Unit (APU) Off

Table A.4: Fuel-Type Input in MOVES

Fuel-Type Input	Value
Fuel Region ID	1570011000
Fuel Year ID	2017
Month Group ID	5
Fuel Formulation ID	3577
Market Share	1
Market Share CV	0.5

Table A.5: Pollutant Information Input in MOVES

Pollutant Process ID	Process ID	Process Name	Pollutant ID	Pollutant Name
102	2	Start Exhaust	1	Total Gaseous Hydrocarbons
202	2	Start Exhaust	2	Carbon Monoxide (CO)
302	2	Start Exhaust	3	Oxides of Nitrogen (NO_x)
502	2	Start Exhaust	5	Methane (CH_4)
602	2	Start Exhaust	6	Nitrous Oxide (N_2O)
702	2	Start Exhaust	32	Sulfur Dioxide (SO_2)
9002	2	Start Exhaust	90	Atmospheric CO_2
9102	2	Start Exhaust	91	Total Energy Consumption
9802	2	Start Exhaust	98	CO_2 Equivalent

APPENDIX B: COMPARISON OF MOVES AND EMFAC RESULTS

Table B.1: Comparison of Emissions Rate of Carbon Dioxide Equivalent (CO_2-e) for MOVES2014a and EMFAC2014 (Based on Sacramento County, Temperature 70°F, Humidity 50%, May 2017)

Vehicle Type	Average Speed	CO2-e Emissions Rate (g/vehicle/mi.)		
		MOVES2014a Average Speed	MOVES2014a Constant Speed	EMFAC2014 Constant Speed
Passenger car (PC)	5 mph	1,033	1,342	991
	15 mph	496	447	566
	25 mph	379	301	375
	35 mph	320	263	288
	45 mph	298	204	257
	55 mph	288	274	266
	65 mph	288	301	320
	75 mph	314	261	343
Sport utility vehicle (SUV)	5 mph	1,315	1,625	1,162
	15 mph	641	542	663
	25 mph	498	373	439
	35 mph	423	329	338
	45 mph	400	332	301
	55 mph	390	347	312
	65 mph	398	388	375
	75 mph	440	437	402
Light-duty truck (LDT)	5 mph	1,750	2,066	1,361
	15 mph	906	689	805
	25 mph	721	484	612
	35 mph	604	482	552
	45 mph	562	375	511
	55 mph	545	486	548
	65 mph	552	572	552
	75 mph	594	612	545
Heavy-duty truck (HDT)	5 mph	3,678	6,162	3,274
	15 mph	1,642	2,054	2,443
	25 mph	1,228	1,580	1,923
	35 mph	985	1,129	1,719
	45 mph	835	878	1,585
	55 mph	710	638	1,499
	65 mph	658	540	1,483
	75 mph	700	468	1,483

Table B.2: Comparison of Emissions Rate of Nitrogen Oxides (NO_x) for MOVES2014a and EMFAC2014 (Based on Sacramento County, Temperature 70°F, Humidity 50%, May 2017)

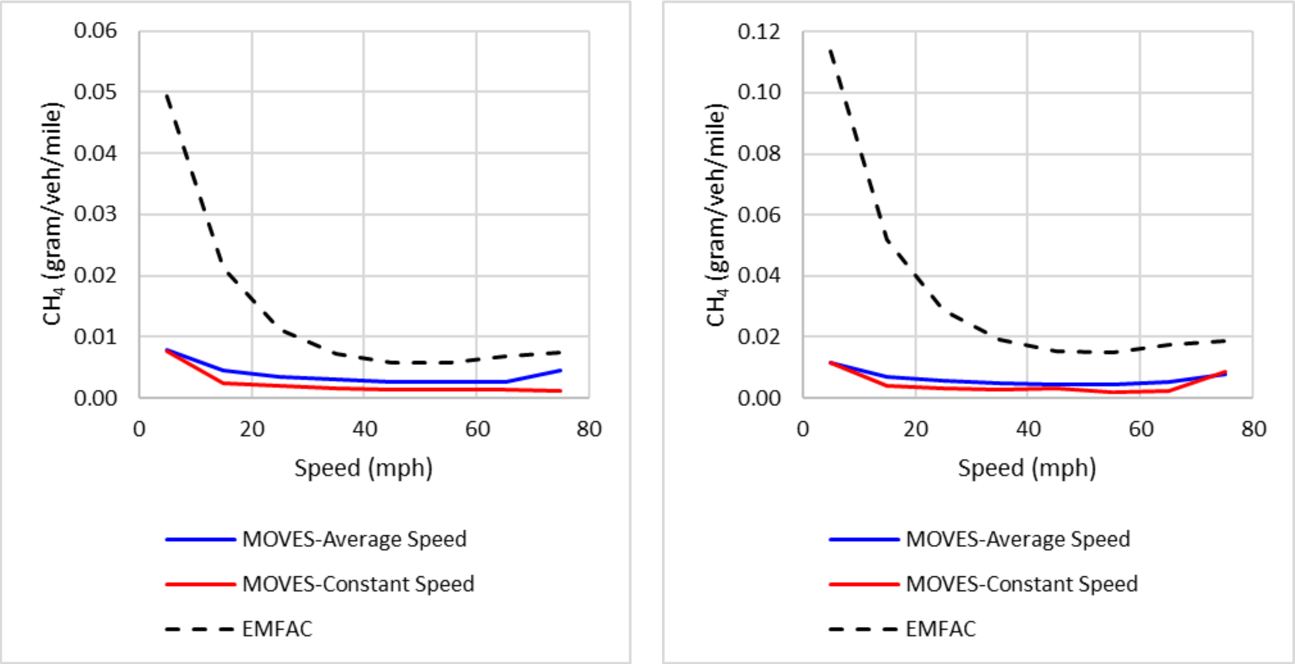
Vehicle Type	Average Speed	NO_x Emissions Rate (g/vehicle/mi.)		
		MOVES2014a Average Speed	MOVES2014a Constant Speed	EMFAC2014
Passenger car (PC)	5 mph	0.3261	0.3589	0.1404
	15 mph	0.2522	0.1196	0.1074
	25 mph	0.2290	0.1121	0.0884
	35 mph	0.1989	0.1216	0.0780
	45 mph	0.1932	0.0945	0.0735
	55 mph	0.2002	0.1722	0.0739
	65 mph	0.2151	0.2111	0.0794
	75 mph	0.2632	0.1829	0.0817
Sport utility vehicle (SUV)	5 mph	0.5503	0.6058	0.3705
	15 mph	0.4435	0.2019	0.2739
	25 mph	0.4130	0.2085	0.2230
	35 mph	0.3779	0.2188	0.1979
	45 mph	0.3858	0.2835	0.1903
	55 mph	0.4057	0.3247	0.1977
	65 mph	0.4500	0.3796	0.2224
	75 mph	0.5666	0.5848	0.2321
Light-duty truck (LDT)	5 mph	5.6451	6.5622	2.7923
	15 mph	2.5628	2.1874	2.9182
	25 mph	1.8506	1.6037	3.1063
	35 mph	1.4672	1.4258	3.3655
	45 mph	1.2766	1.1089	3.6438
	55 mph	1.2138	1.1313	3.9313
	65 mph	1.2236	1.1793	4.2262
	75 mph	1.3780	1.3779	4.3001
Heavy-duty truck (HDT)	5 mph	14.8353	25.7675	18.3558
	15 mph	6.3497	8.5892	10.4298
	25 mph	4.5614	5.8627	6.4574
	35 mph	3.6358	4.1876	5.3594
	45 mph	3.0559	3.2571	4.8405
	55 mph	2.5947	2.3289	4.6302
	65 mph	2.4067	1.9706	4.6113
	75 mph	2.5637	1.7089	4.6113

Table B.3: Comparison of Emissions Rate of Sulfur Oxides (SO_x) for MOVES2014a and EMFAC2014 (Based on Sacramento County, Temperature 70°F, Humidity 50%, May 2017)

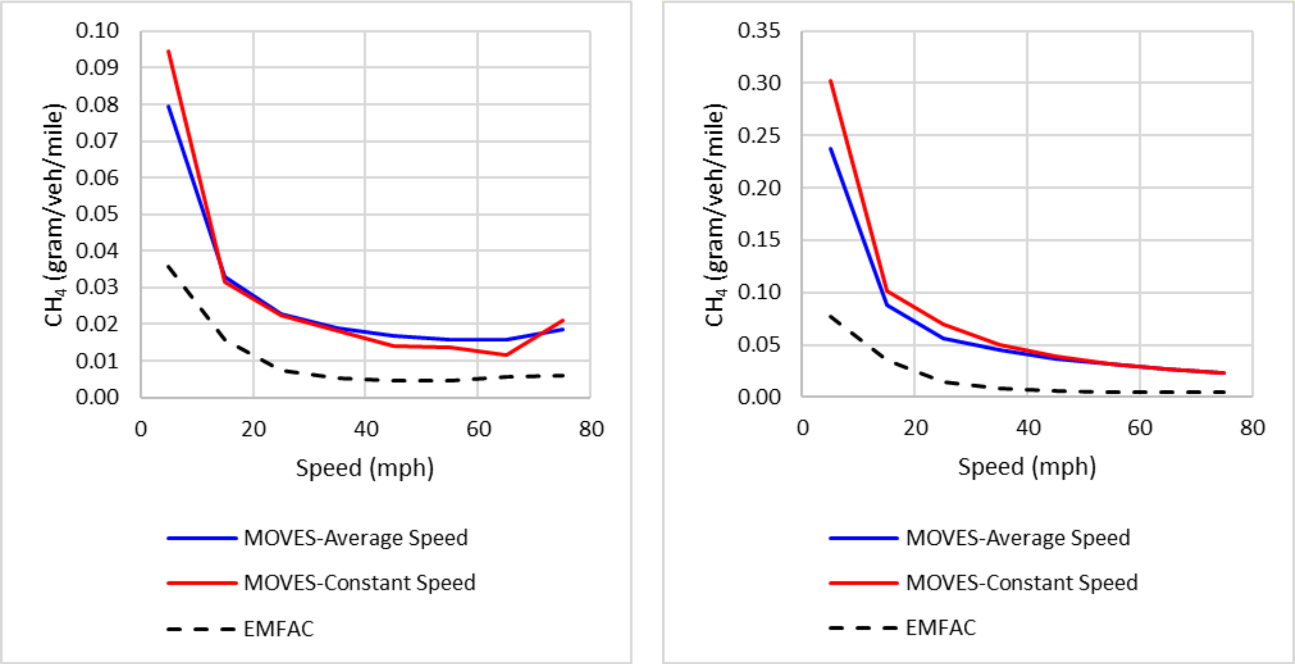
Vehicle Type	Average Speed	SO_x Emissions Rate (g/vehicle/mi.)		
		MOVES2014a Average Speed	MOVES2014a Constant Speed	EMFAC2014
Passenger car (PC)	5 mph	0.0062	0.0080	0.0099
	15 mph	0.0030	0.0027	0.0057
	25 mph	0.0023	0.0018	0.0038
	35 mph	0.0019	0.0016	0.0029
	45 mph	0.0018	0.0012	0.0026
	55 mph	0.0017	0.0016	0.0027
	65 mph	0.0017	0.0018	0.0032
	75 mph	0.0019	0.0016	0.0034
Sport utility vehicle (SUV)	5 mph	0.0079	0.0097	0.0117
	15 mph	0.0038	0.0032	0.0067
	25 mph	0.0030	0.0022	0.0044
	35 mph	0.0025	0.0020	0.0034
	45 mph	0.0024	0.0020	0.0030
	55 mph	0.0023	0.0021	0.0031
	65 mph	0.0024	0.0023	0.0038
	75 mph	0.0026	0.0026	0.0040
Light-duty truck (LDT)	5 mph	0.0150	0.0177	0.0130
	15 mph	0.0078	0.0059	0.0077
	25 mph	0.0062	0.0041	0.0058
	35 mph	0.0052	0.0041	0.0053
	45 mph	0.0048	0.0032	0.0049
	55 mph	0.0047	0.0042	0.0052
	65 mph	0.0047	0.0049	0.0053
	75 mph	0.0051	0.0052	0.0052
Heavy-duty truck (HDT)	5 mph	0.0314	0.0527	0.0312
	15 mph	0.0140	0.0176	0.0233
	25 mph	0.0105	0.0135	0.0183
	35 mph	0.0084	0.0096	0.0164
	45 mph	0.0071	0.0075	0.0151
	55 mph	0.0061	0.0055	0.0143
	65 mph	0.0056	0.0046	0.0141
	75 mph	0.0060	0.0040	0.0141

Table B.4: Comparison of Emissions Rate of Particulate Matter 2.5 Microns ($PM_{2.5}$) for MOVES2014a and EMFAC2014 (Based on Sacramento County, Temperature 70°F, Humidity 50%, May 2017)

Vehicle Type	Average Speed	$PM_{2.5}$ Emissions Rate (g/vehicle/mi.)		
		MOVES2014a Average Speed	MOVES2014a Constant Speed	EMFAC2014
Passenger car (PC)	5 mph	0.0329	0.0114	0.0105
	15 mph	0.0171	0.0051	0.0045
	25 mph	0.0125	0.0053	0.0024
	35 mph	0.0088	0.0036	0.0015
	45 mph	0.0065	0.0029	0.0012
	55 mph	0.0052	0.0041	0.0012
	65 mph	0.0047	0.0033	0.0014
	75 mph	0.0052	0.0028	0.0016
Sport utility vehicle (SUV)	5 mph	0.0338	0.0093	0.0184
	15 mph	0.0190	0.0044	0.0082
	25 mph	0.0143	0.0036	0.0044
	35 mph	0.0101	0.0032	0.0029
	45 mph	0.0076	0.0028	0.0024
	55 mph	0.0061	0.0046	0.0023
	65 mph	0.0058	0.0042	0.0027
	75 mph	0.0069	0.0054	0.0029
Light-duty truck (LDT)	5 mph	0.3304	0.2856	0.0958
	15 mph	0.1359	0.0967	0.0516
	25 mph	0.0903	0.0608	0.0324
	35 mph	0.0681	0.0491	0.0240
	45 mph	0.0603	0.0383	0.0209
	55 mph	0.0561	0.0588	0.0212
	65 mph	0.0547	0.0581	0.0257
	75 mph	0.0536	0.0533	0.0277
Heavy-duty truck (HDT)	5 mph	0.7471	0.7907	0.2048
	15 mph	0.2939	0.2663	0.1225
	25 mph	0.1998	0.2012	0.0727
	35 mph	0.1581	0.1443	0.0585
	45 mph	0.1321	0.1125	0.0549
	55 mph	0.1164	0.1108	0.0620
	65 mph	0.1028	0.0938	0.0654
	75 mph	0.0954	0.0812	0.0654

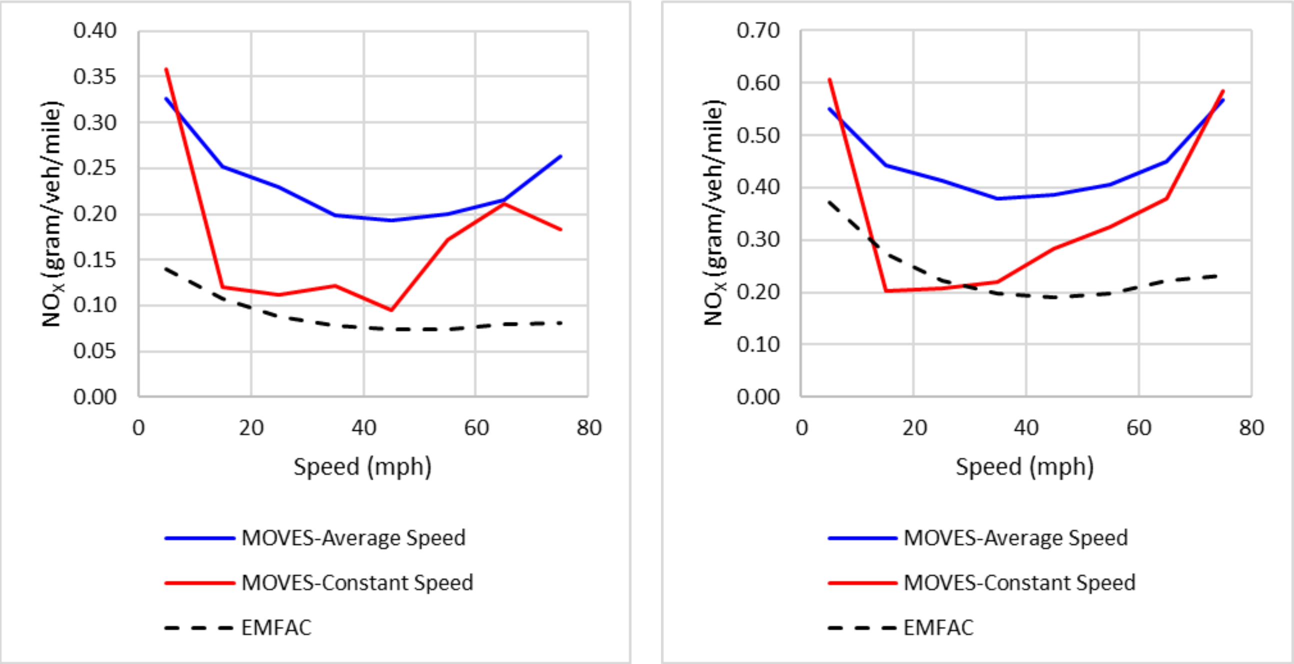


(a) Passenger car **(b) Sport utility vehicle**

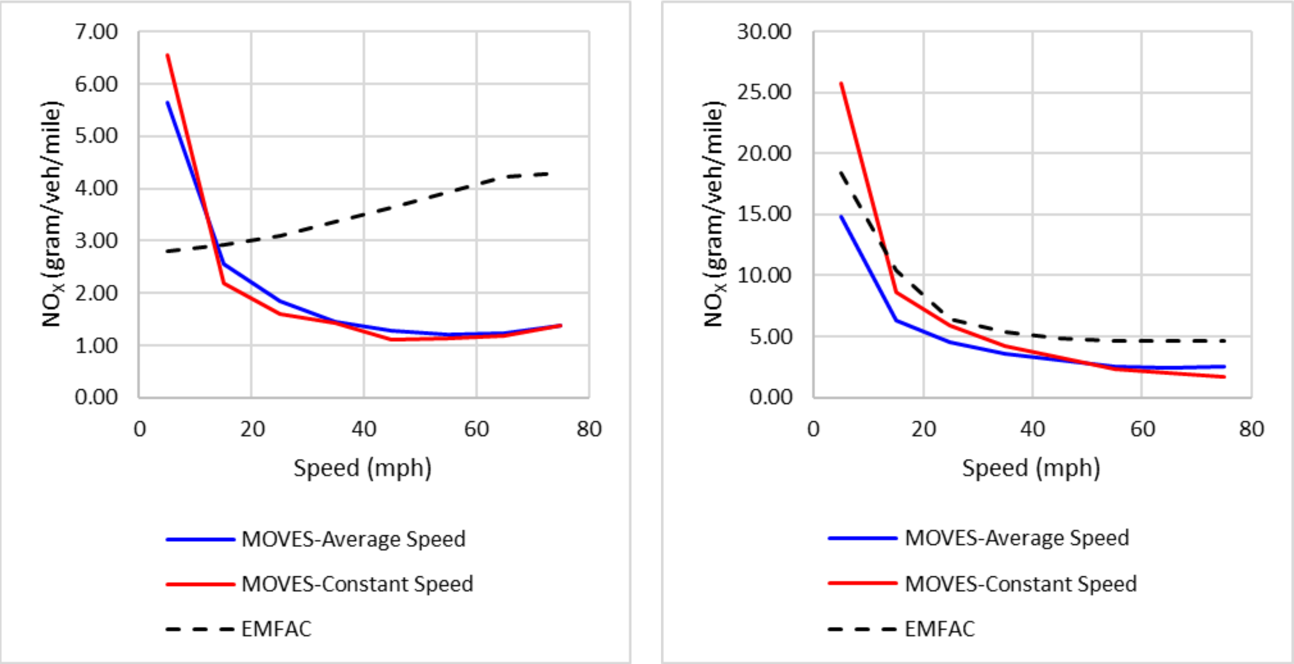


(c) Light-duty truck **(d) Heavy-duty truck**

Figure B.1: Comparison of CH_4 by speed for *MOVES* and *EMFAC.*

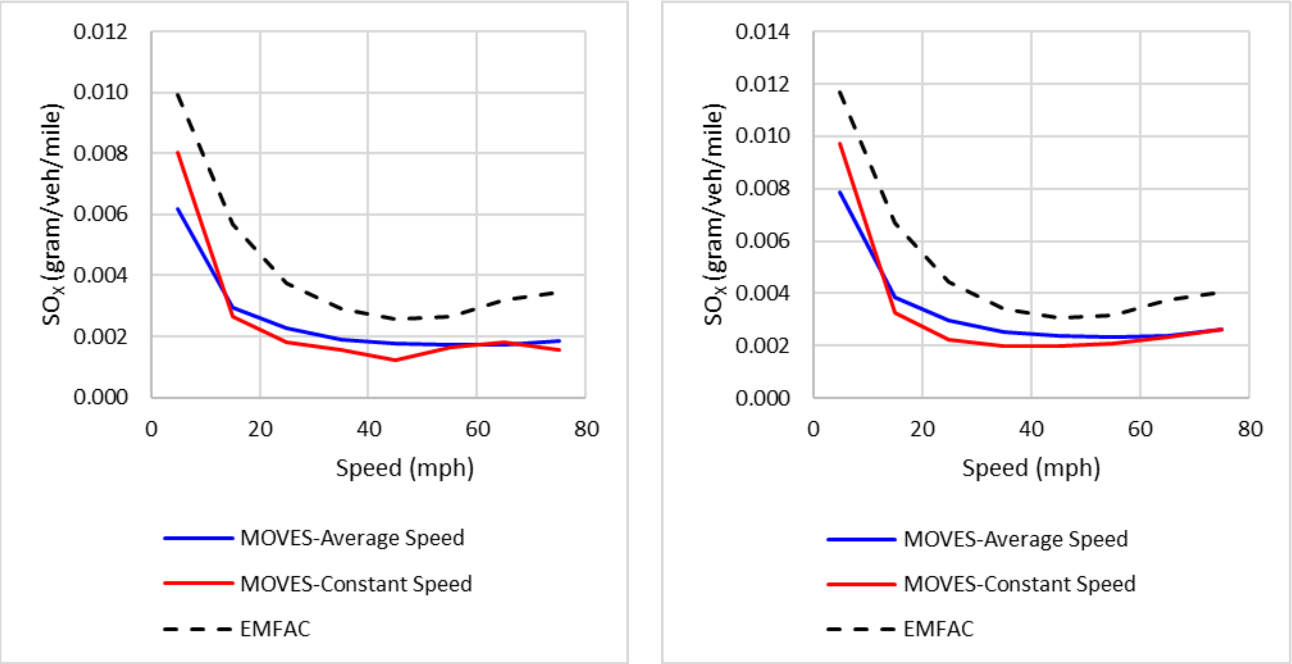


(a) Passenger car **(b) Sport utility vehicle**

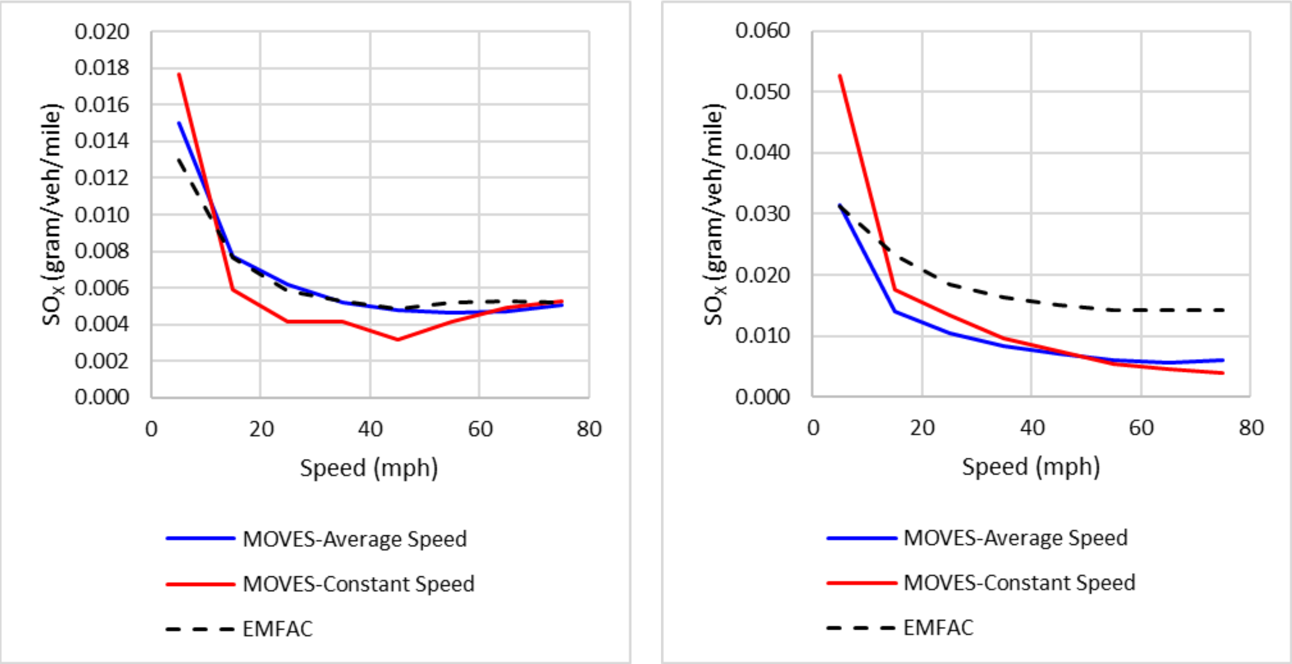


(c) Light-duty truck **(d) Heavy-duty truck**

Figure B.2: Comparison of NO_x by speed for *MOVES* and *EMFAC*.

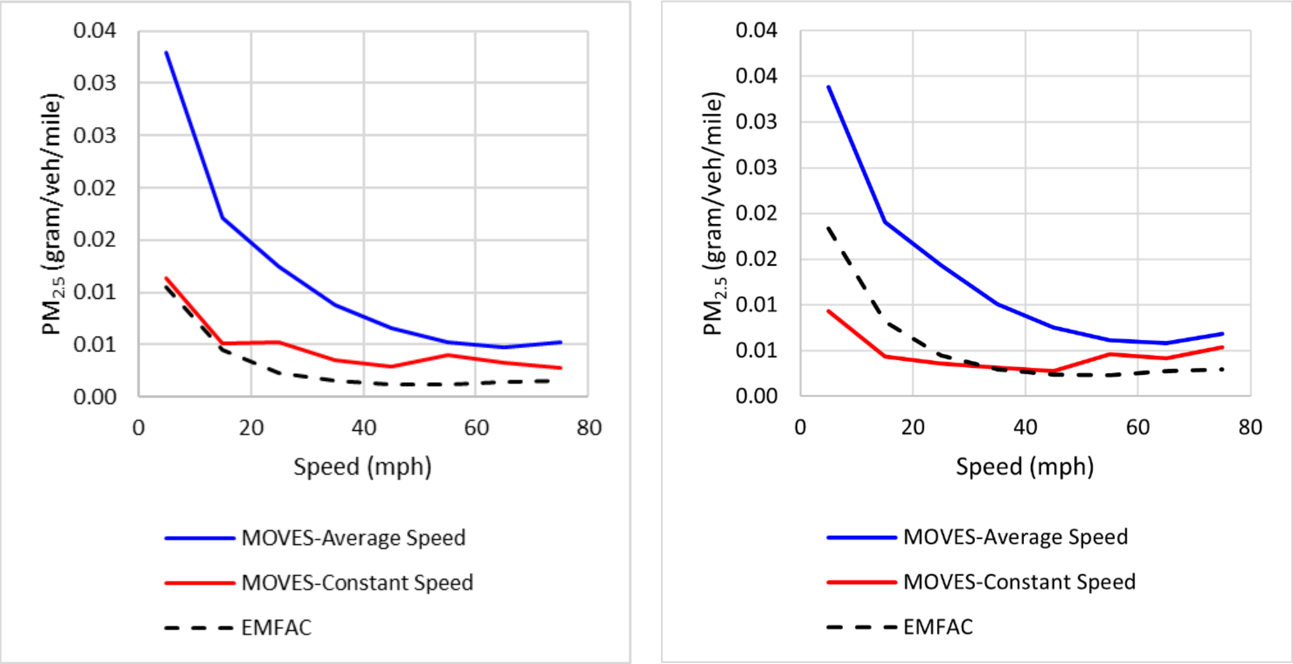


(a) Passenger car **(b) Sport utility vehicle**



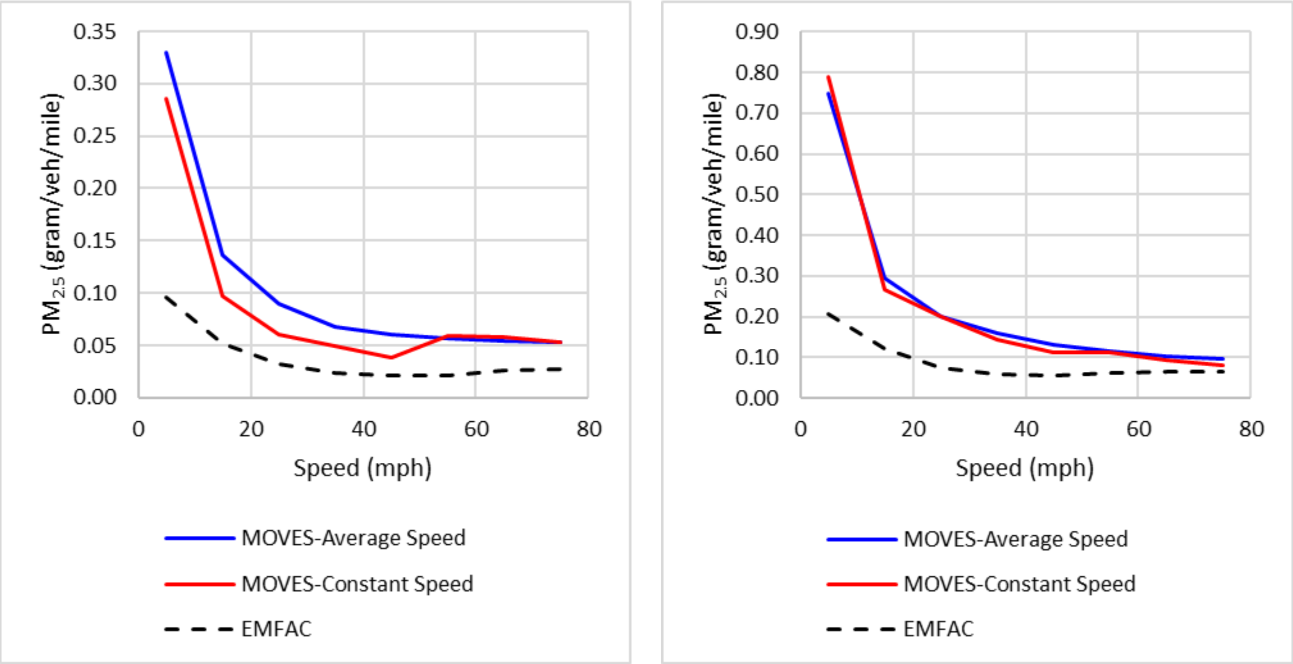
(c) Light-duty truck **(d) Heavy-duty truck**

Figure B.3: Comparison of SO_x by speed for *MOVES* and *EMFAC.*



(a) Passenger car

(b) Sport utility vehicle

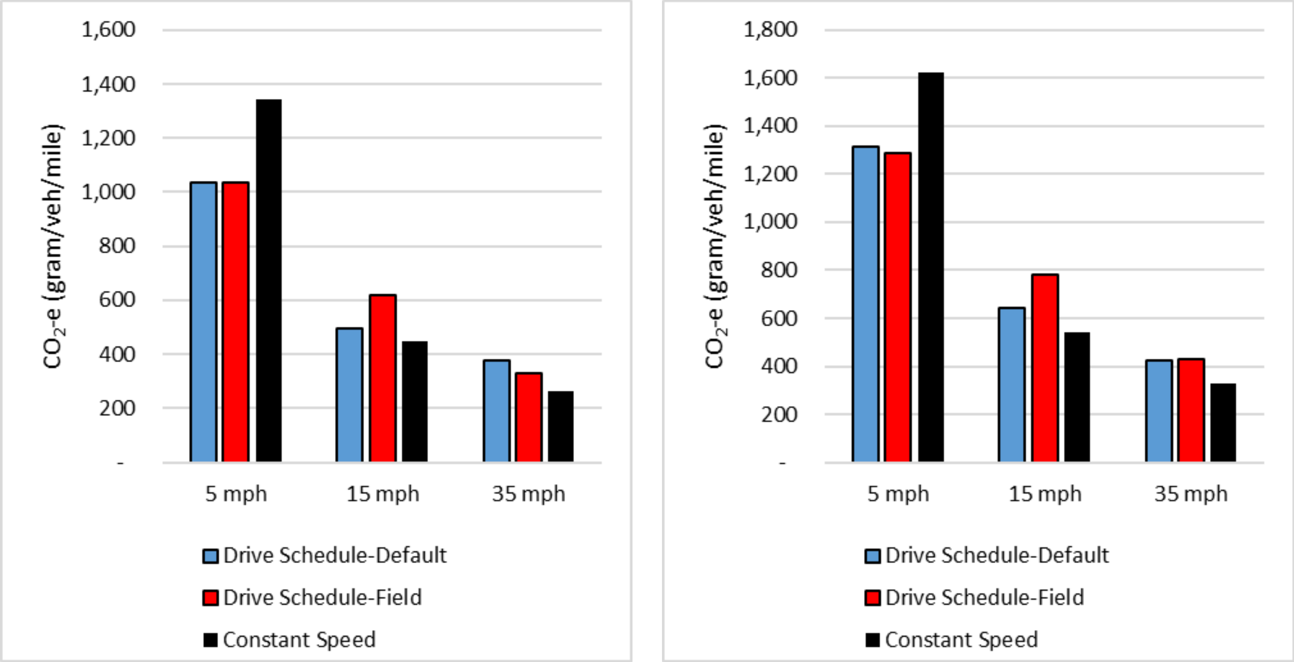


(c) Light-duty truck

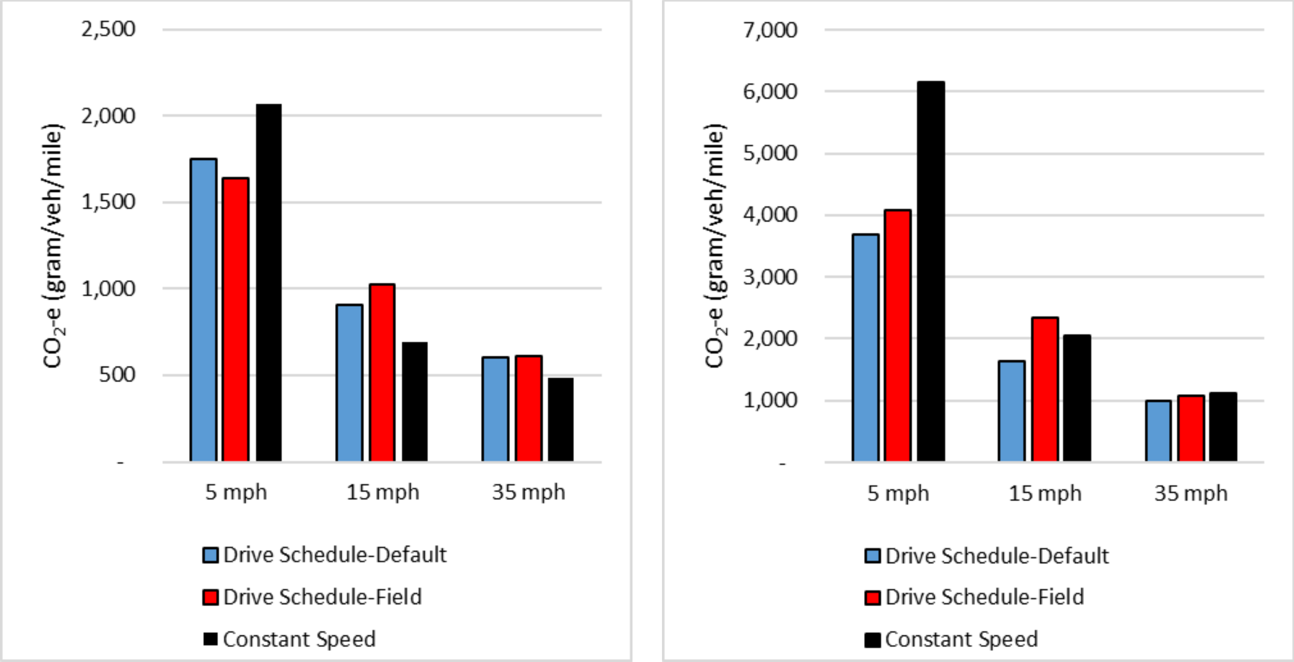
(d) Heavy-duty truck

Figure B.4: Comparison of PM$_{2.5}$ by speed for *MOVES* and *EMFAC*.

APPENDIX C: SIMULATION RESULTS OF THE DRIVE CYCLES

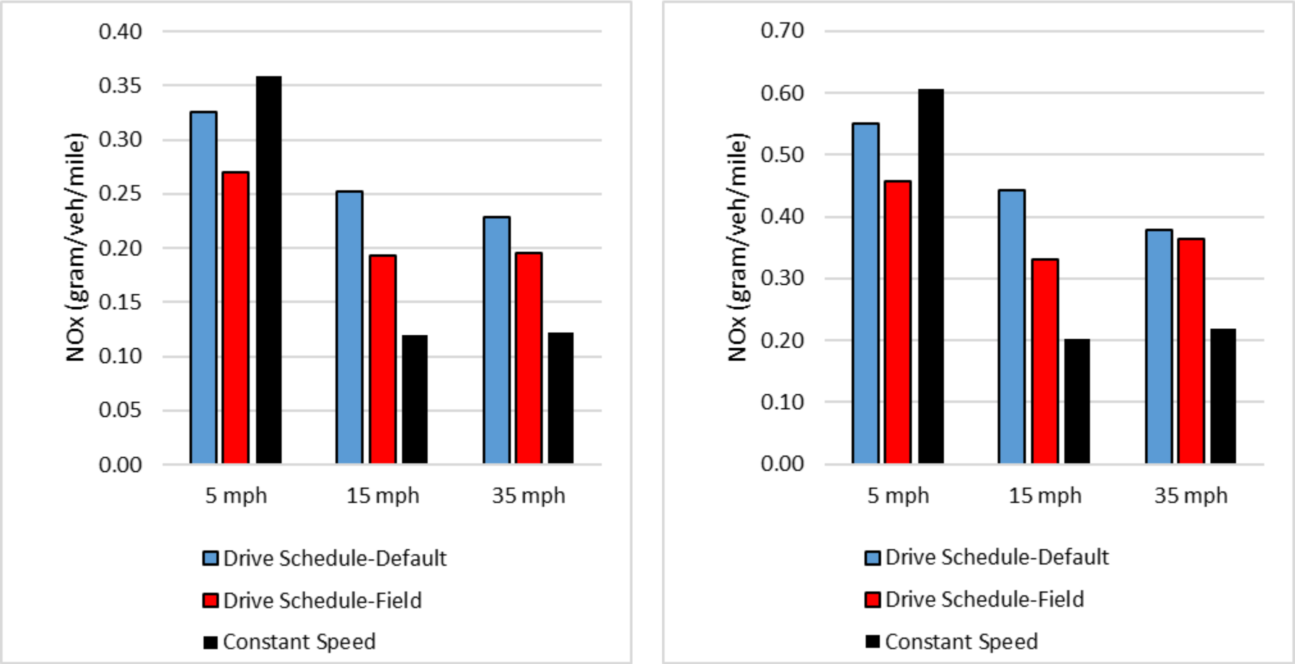


(a) Passenger car **(b) Sport utility vehicle**

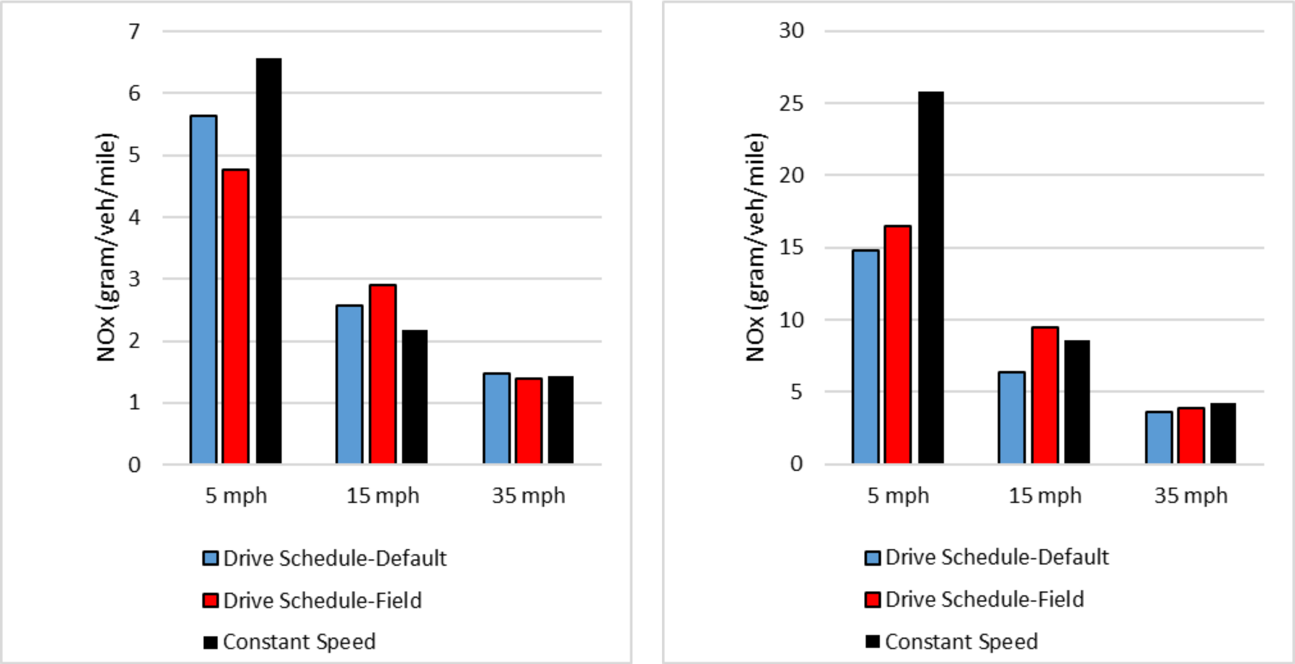


(c) Light-duty truck **(d) Heavy-duty truck**

Figure C.1: Comparison of CO_2-e for *MOVES* drive cycles and constant speeds.

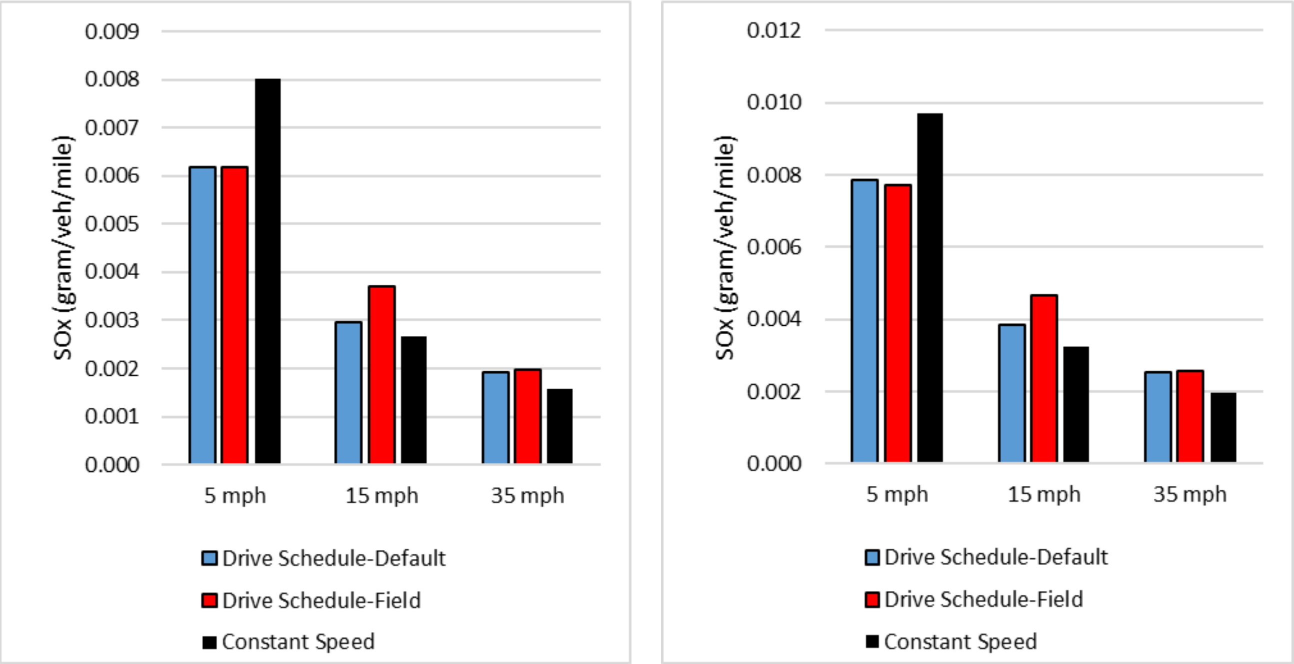


(a) Passenger car **(b) Sport utility vehicle**

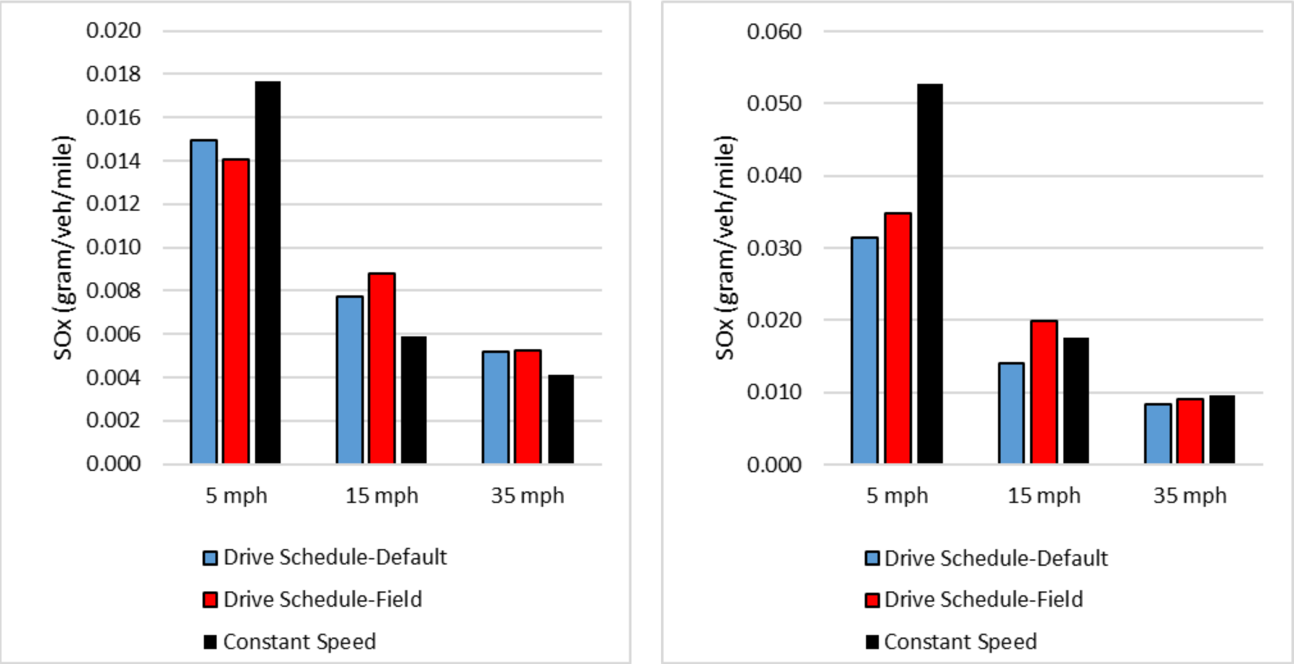


(c) Light-duty truck **(d) Heavy-duty truck**

Figure C.2: Comparison of NO_x for *MOVES* drive cycles and constant speeds.

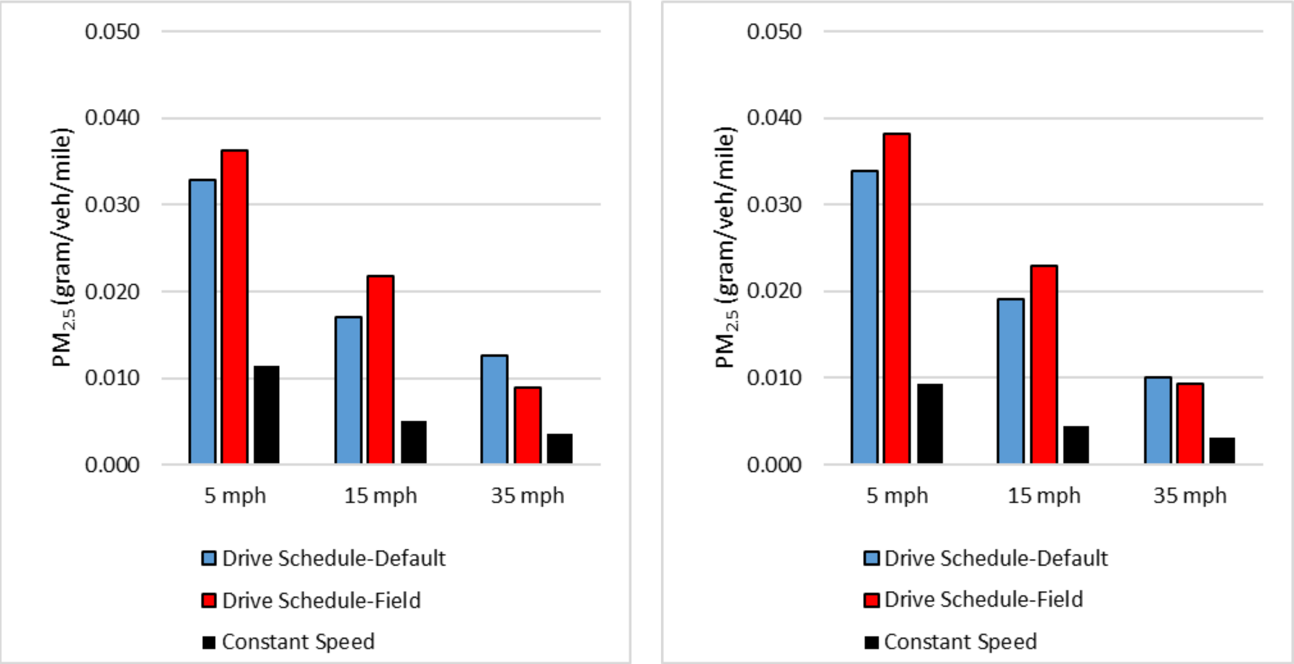


(a) Passenger car **(b) Sport utility vehicle**

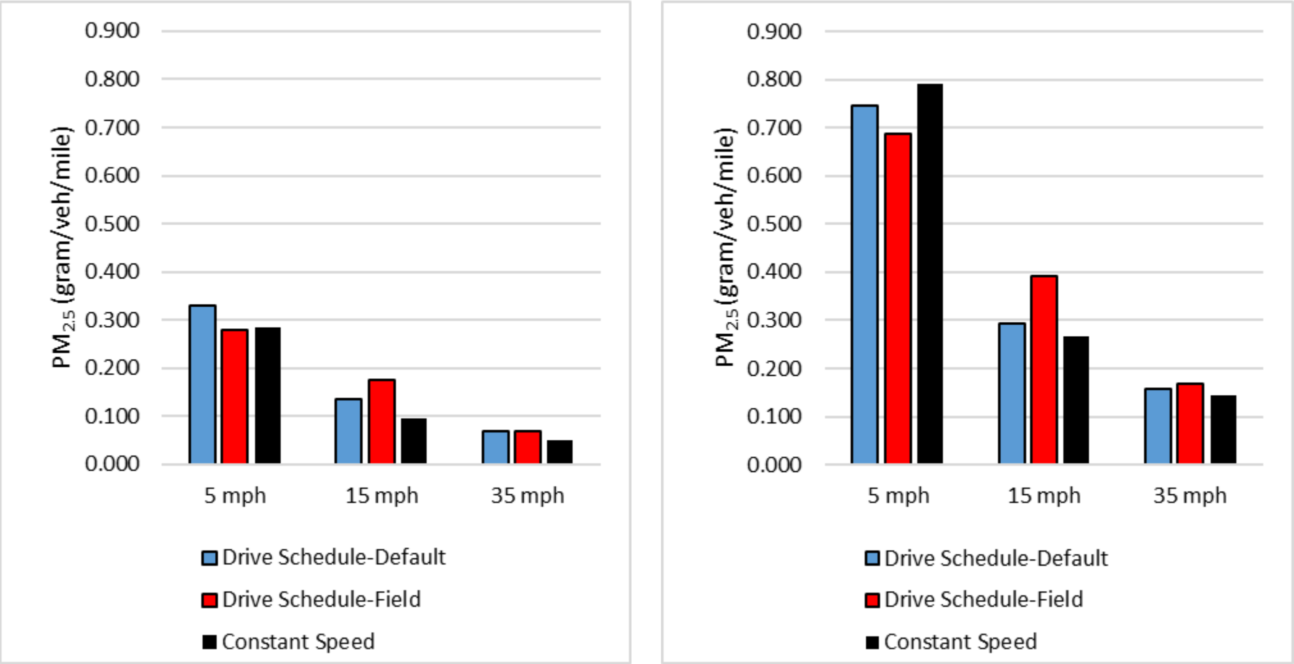


(c) Light-duty truck **(d) Heavy-duty truck**

Figure C.3: Comparison of SO_2 for *MOVES* drive cycles and constant speeds.

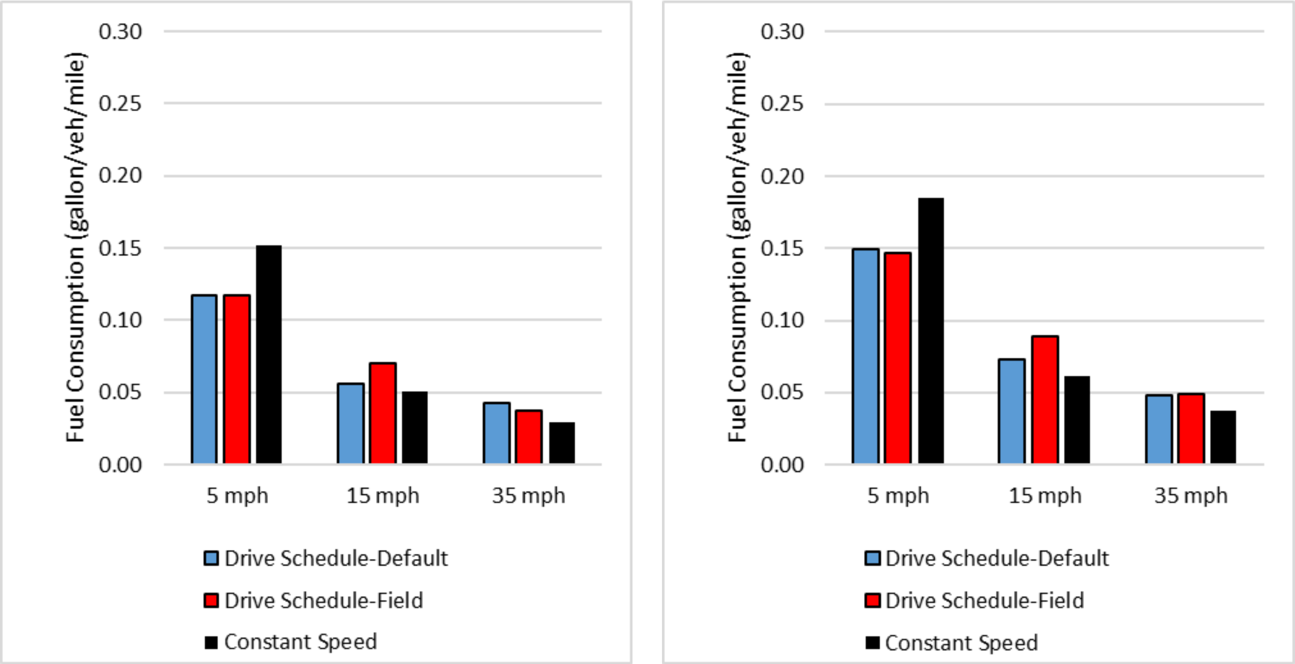


(a) Passenger car **(b) Sport utility vehicle**

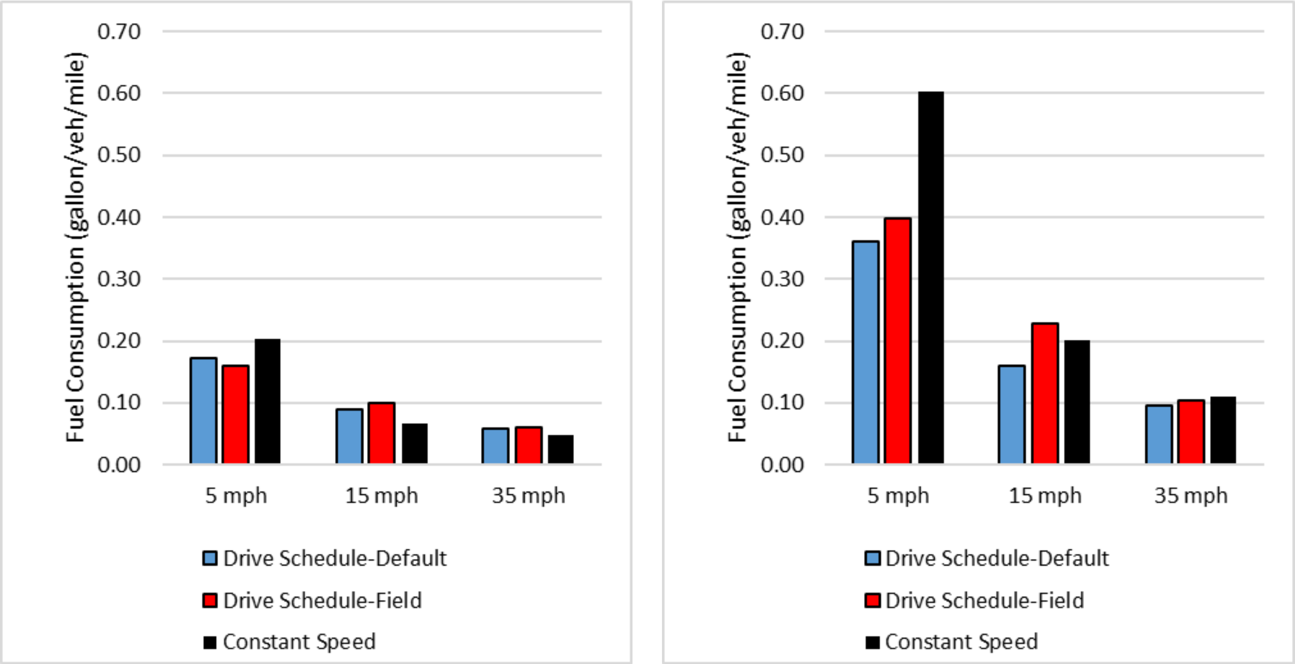


(c) Light-duty truck **(d) Heavy-duty truck**

Figure C.4: Comparison of $PM_{2.5}$ for *MOVES* drive cycles and constant speeds.



(a) Passenger car **(b) Sport utility vehicle**



(c) Light-duty truck **(d) Heavy-duty truck**

Figure C.5: Comparison of fuel consumption for *MOVES* drive cycles and constant speeds.