Maintenance of Traffic Carbon Footprint: Quantification of Environmental Impacts from the Project-Level Construction Work Zone Framework

Final Report
December 2024

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16. Abstract

Construction work zones (CWZs) can contribute to greenhouse gas emissions through several means, including excess vehicle fuel use due to congestion, traffic slowdowns, pilot car operations, and drivers using longer alternative routes to avoid CWZs. To determine the environmental impacts of CWZs, a recently completed study by the University of California Pavement Research Center (UCPRC) proposed a life-cycle assessment (LCA) framework for quantifying the fuel use and environmental impacts of vehicles traveling in CWZs under various traffic closure conditions. The goal of this current study was to demonstrate the use of the UCPRC CWZ framework. A simple tool that can compute the global warming (GW, in terms of CO_2-e) for different CWZ scenarios and closure types for urban, suburban and rural conditions was developed to do the calculations and has been made available with this report. The closure types considered for one lane-mile of construction of a rigid pavement included a 10-hour nighttime closure, a 24-hour continuous closure with 8-hour and 24-hour work shifts, and a closure involving pilot vehicle operation. The cradle-to-lay environmental impacts of rigid pavement construction were not computed in this study. A decision support framework was proposed to help users identify the most GW-efficient closure type for a given CWZ scenario and road setting.

The case study results showed that daytime CWZ closures significantly contributed to GW mainly due to high traffic volumes, traffic congestion, and long CWZ queues during daytime rush hours. The greater productivity of 24-hour shifts instead of 8-hour shifts in a 24-hour continuous closure significantly reduced the GW results, though it still did not lower GW to the levels achieved by 10-hour closures. In the urban setting, a reduction in GW was seen for 10-hour nighttime closures due to fuel-efficient driving speeds. The CWZ GW was determined to be significantly high in urban settings in the 24-hour continuous closure scenario and was highest for the 8-hour work shift. The suburban and rural settings showed similar GW impacts for the closure types considered in this study. Due to higher productivity rates with 24-hour work shifts compared to 8-hour work shifts in a 24-hour continuous closure, significant GW reduction was seen in all three road type settings. The CWZ fatality indicator calculator showed that 24-hour closures with 24 hours of continuous work were about as safe as 10-hour nighttime closures, which should be considered in decision support.

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MAINTENANCE OF TRAFFIC – QUANTIFICATION OF ENVIRONMENTAL IMPACTS FROM THE PROJECT-LEVEL CONSTRUCTION WORK ZONE FRAMEWORK

Final Report
December 2024

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EXECUTIVE SUMMARY

The use stage is often overlooked in pavement life-cycle assessments (LCAs). However, on routes with higher traffic volumes, the impact of pavement condition and operations during the use stage can significantly exceed the effects of traditionally considered stages such as materials, material transportation, and construction. Construction work zones (CWZs) can contribute to greenhouse gas emissions through several means, including excess vehicle fuel use due to congestion, traffic slowdowns, pilot car operations, and drivers' use of longer alternative routes to avoid CWZs. To determine whether and to what extent a CWZ contributes to environmental impacts, a recently completed study by the University of California Pavement Research Center (UCPRC) proposed an LCA framework to quantify the fuel use and environmental impacts of vehicles traveling in CWZs under various traffic closure conditions for highway maintenance and rehabilitation projects.

The goal of this current study was to demonstrate the use of the UCPRC CWZ framework. A simple tool that can compute the global warming (GW, in terms of CO_2-e) for different CWZ scenarios and closure types for urban, suburban and rural conditions was developed to do the calculations and has been made available with this report. The closure types considered for one lane-mile of construction of a rigid pavement included a 10-hour nighttime closure, a 24-hour continuous closure with 8-hour and 24-hour work shifts, and a closure involving pilot vehicle operation. The cradle-to-lay environmental impacts of rigid pavement construction were not computed in this study. A decision support framework was proposed to help users identify the most GW-efficient closure type for a given CWZ scenario and road setting.

The case study results showed that daytime CWZ closures significantly contributed to GW mainly due to high traffic volumes, traffic congestion, and long CWZ queues during daytime rush hours. The greater productivity of 24-hour shifts instead of 8-hour shifts in a 24-hour continuous closure significantly reduced the GW results, though it still did not lower GW to the levels achieved by 10-hour closures. In the urban setting, a reduction in GW was seen for 10-hour nighttime closures due to fuel-efficient driving speeds. The CWZ GW was determined to be significantly high in urban settings in the 24-hour continuous closure scenario and was highest for the 8-hour work shift. The suburban and rural settings showed similar GW impacts for the closure types considered in this study. Due to higher productivity rates with 24-hour work shifts compared to 8-hour work shifts in a 24-hour continuous closure, significant GW reduction was seen in all three road type settings. The CWZ fatality indicator calculator showed that 24-hour closures with 24 hours of continuous work were about as safe as 10-hour nighttime closures, which should be considered in decision support.

LIST OF ABBREVIATIONS

AADT	average annual daily traffic
CO_2-e	carbon dioxide equivalent
CWZ	construction work zone
EFC	excess fuel consumption
FHWA	Federal Highway Administration
GW	global warming
HDT	heavy duty diesel truck
LCA	life-cycle assessment
LCCA	life-cycle cost analysis
LDT	light duty truck
U.S. EPA's MOVES	United States Environmental Protection Agency's Motor Vehicle Emission Simulator
PC	passenger car
$PM_{2.5}$	particulate matter (size smaller than 2.5 micron)
SUV	sport utility vehicle
UCPRC	University of California Pavement Research Center
VMT	vehicle miles traveled

CONVERSION FACTORS

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).

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 (2,000 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

INTRODUCTION

The use stage is typically not considered in pavement life-cycle assessments (LCA), and on routes with higher traffic levels the influence of the pavement condition and pavement operations in the use stage can be far larger than the typically considered materials, material transportation, and construction stages (Wang et al. 2014). In addition to pavement-vehicle interaction, an important consideration in the use stage is the environmental impacts that arise from construction work zones (CWZs). A CWZ is a designated area where construction and maintenance activities are being carried out on or near a roadway. Such work zones are established to ensure the safety of construction workers, drivers, and pedestrians while construction work is in progress. CWZs can contribute to greenhouse gas (GHG) emissions through several means, including excess fuel use due to congestion, traffic slowdowns, pilot car operations, and CWZ avoidance or traffic rerouting resulting in longer alternative driving routes.

To determine if and how much a CWZ influences environmental impacts, a study was recently completed by the University of California Pavement Research Center (UCPRC), funded by the California Department of Transportation (Caltrans), in which an LCA framework was proposed that quantifies the fuel use and environmental impacts of vehicles traveling in CWZs under different traffic closure conditions for highway maintenance and rehabilitation projects (Kim et al. 2022). The scenarios considered were freeways, multilane highways, and two-lane highways with pilot car operations under low to high traffic congestion levels. The simulations showed that a heavily congested freeway with a CWZ showed increases of 85% fuel consumption, 86% CO_2-e, and 128% $PM_{2.5}$ when compared to a 65 mph free-flow vehicle speed with no CWZ. In the case of a multilane highway, a heavily congested CWZ scenario showed increases of 85% fuel consumption, 88% CO_2-e, and 129% $PM_{2.5}$ when compared to a no-CWZ, no-congestion (55 mph free-flow speed) scenario. Additionally, reducing traffic congestion in a CWZ from heavy (average speed of 5 mph) to medium (average speed of 25 mph on a freeway section and 15 mph on a multilane road) led to a 40% decrease in fuel consumption on the freeway and a 33% decrease on the multilane highway. The results of the pilot car operation scenario showed that implementing a one-lane closure with pilot car operation on a two-lane road could increase fuel consumption by 13% due to prolonged idling and the slow movement of vehicles trailing the pilot car when compared to a free-flow, no-CWZ case. In another study by Huang et al. (2024), it was determined through simulation results that freeway work zones affect vehicle fuel consumption significantly.

The authors of the study presented in this report were unable to find any studies in the literature that considered quantification of vehicle fuel use and environmental impacts under different CWZ scenarios in a life-cycle perspective.

Goal and Scope of the Study

The goal of this study was to demonstrate the use of the CWZ framework developed by Kim et al. (2022). The scope and approach for this study included the following:

- Identify three typical US cases (highway routes) in urban, suburban, and rural settings

- Collect local traffic data for the identified highway routes
- Use existing models such as Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) (Lee et al. 2005) to determine the traffic implications of up to three strategies in each case
- Assess the environmental and safety impacts of the various scenarios based on vehicle delays using the CWZ framework (Kim et al. 2022), including estimating avoided impacts due to no-show traffic in the CWZ and detour traffic
- Develop a decision tree to allow agencies to assess environmental impacts for their locations and to make decisions based on well-informed situations

A simple Microsoft Excel-based tool that can compute the global warming (GW, in terms of CO_2-e) for different CWZ scenarios and closure types for urban, suburban, and rural conditions considered in this study was also developed for the case studies. The tool was included with the deliverables, although tool development and delivery were not part of the scope of the project. A development process for the decision support framework was then proposed that can help users identify which closure type in a CWZ scenario for a particular region/road setting is most beneficial in terms of lower GW.

METHODOLOGY

The construction strategy alternatives were determined by calculating the number of closures per scenario, considering various highway configurations, traffic conditions, and construction schedules. Using the CWZ traffic analysis approach, the additional hourly traffic delays on both the CWZ and the detour roads due to lane closures in the CWZs were calculated. These delays were then converted into increased gasoline and diesel consumption, termed excess fuel consumption (EFC). The environmental impact of each scenario was subsequently assessed using the emission rates derived from the LCA of the CWZ study performed by Kim et al. (2022).

The vehicle types selected for case study/demonstration purposes are the same as those used in Kim et al. (2022): a gasoline-powered passenger car (PC), a gasoline-powered sport utility vehicle (SUV), a light-duty diesel truck (LDT), and a heavy-duty diesel truck (HDT). These vehicles can be mapped in the United States Environmental Protection Agency's (EPA's) Motor Vehicle Emission Simulator (MOVES) (U.S. EPA 2015) to a passenger car, a passenger truck (personal use), a light commercial truck, and a single-unit short-haul truck.

The study consists of three cases: (1) urban, (2) suburban, and (3) rural highways. Each case is described below:

- **Case 1: Urban**. The urban highway section represents high-traffic multilane urban highways with eight lanes or more in two directions. This section typically shows two peak traffic periods: one in the morning and the other in the afternoon in each traffic direction during weekdays.
- **Case 2: Suburban**. The suburban highway section represents medium-traffic four-lane highways (two lanes in each direction) connecting major and minor cities. This section typically shows one peak period in each direction: the morning peak period in the inbound direction (suburban to city) and the afternoon peak period in the outbound direction (city to suburban) during weekdays.
- **Case 3: Rural**. The rural highway section represents low-traffic two-lane highways (one lane in each direction) connecting small cities or towns. This section typically shows similar hourly traffic distribution patterns to that of the suburban highway section but with a much lower average annual daily traffic (AADT).

Reconstruction of 1 lane-mile of 8 in. thick rigid pavement with 40 years of design life was assumed for all cases. The construction activity was assumed to be lane replacement using rapid strength concrete. Note that the cradle-to-lay environmental impacts of rigid pavement construction are not computed in this study; rather they are mentioned to determine the closure type and time of the construction activity so that the vehicles' EFC due to CWZ could be calculated.

Three construction strategies were evaluated in this study, with each strategy having two work shift scenarios.

1. **10-hour Nighttime (Partial) Closure**. The traffic lanes are partially closed during the night (8:00 p.m. to 6:00 a.m.) until the highway construction project is completed. This construction strategy is frequently employed in urban areas with high daytime traffic volumes. The traffic control devices are deployed and removed every evening and morning during this type of closure.
2. **24-hour Continuous Closure**. During the construction period, one roadbed's traffic lanes are fully closed for construction activities. The other roadbed accommodates traffic in both directions through counterflow traffic operations. The lane closure remains until the construction is completed. This strategy is often applied to reconstruction or rehabilitation projects requiring intensive activities for fast and high-quality construction productivity. A drawback of this strategy is that traffic delays could be considerably longer, especially when applied to high-traffic urban highway sections. Two work schedules were considered:
   a. Construction activity progresses for 8 hours per day (single work shift), which is common in many construction projects.
   b. Construction activity progresses for 24 hours (three work shifts) per day, which is often used when work is fast-tracked.
3. **Pilot Vehicle Operation**. In a CWZ section of two-lane highways, one direction/lane is closed for construction, and a pilot vehicle leads traffic in the opposite direction/lane. This setup inevitably leads to idle time for vehicles in the CWZ, as one lane must accommodate traffic in both directions. This approach is typically used in CWZs situated on low-traffic rural highways.

A schematic diagram of the approach adopted in this study is presented in Figure 1.

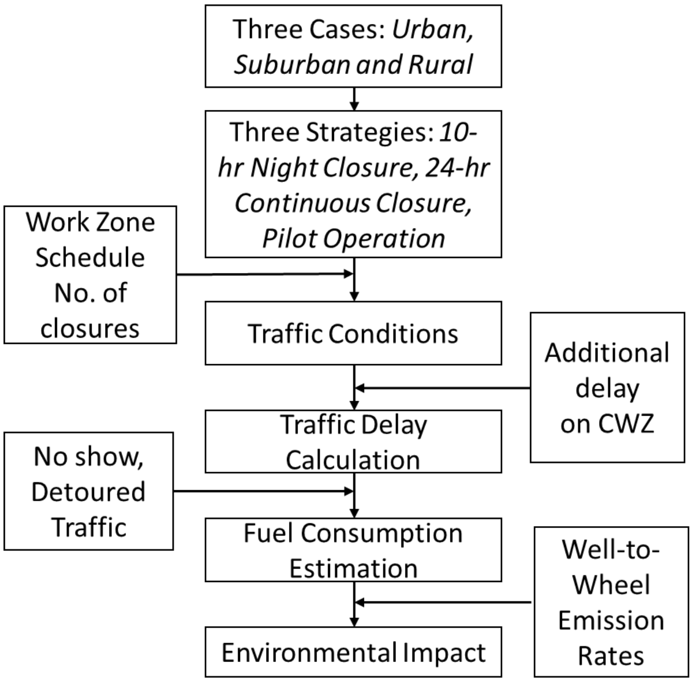

Figure 1. Schematic diagram of study approach

The construction productivity rate for a 10-hour nighttime partial closure is 0.06 miles per closure. Construction productivity rates for 8-hour and 24-hour working shifts are 0.07 and 0.21 miles for a 24-hour continuous closure, respectively. The number of closures for each construction strategy was calculated using the construction productivity rates available in the California Department of Transportation (Caltrans) *Life-Cycle Cost Analysis (LCCA) Procedures Manual* (Caltrans 2013).

Hourly traffic delay and EFC were calculated using the CWZ delay calculation method in the Caltrans version of RealCost (Caltrans 2013), modified from the Federal Highway Administration's (FHWA's) delay calculation concept. The CWZ delay calculation method utilizes a demand-capacity model to determine hourly traffic volumes that exceed the available hourly capacity. This capacity varies based on the proportion of heavy vehicles in the traffic flow, the traffic lane configuration, and the lane closure scheme (the number of lanes closed) on the CWZ section. The CWZ delay is the sum of the additional travel time spent by all vehicles traveling in a CWZ section when demand exceeds capacity.

Fuel consumption is then calculated by the average vehicle's speed and the length of the queue each hour during the construction period. When the traffic volume does not exceed capacity, the CWZ delay is calculated as the additional travel time caused by the difference in speed limits between the no-CWZ and CWZ periods, assuming vehicles travel at a free-flow speed close to the posted speed limit. In most states, agencies lower posted speed limits by 10 to 20 mph in CWZ sections to improve safety and reduce accidents. Thus, when no CWZ delay occurs (demand is less than capacity), travel time on CWZ sections may be slightly longer than in the case of no-CWZ sections, but fuel consumption may increase or decrease depending on the vehicle types. The length of the queue on CWZ sections is calculated by the number of vehicles exceeding the capacity and the density of vehicles per mile (vehicles per mile per lane) each hour. The average traffic speed is assumed to be 5 mph, reflecting frequent stop-and-go status. The fuel consumption per vehicle is calculated by the length of the queue divided by the fuel efficiency (miles per gallon).

Emission rates are different for different vehicle types and their respective speeds. The UCPRC study (Kim et al. 2022) quantified fuel consumption rates and CO_2-e rates for different vehicle types in various speed ranges using the EPA's MOVES for several CWZ scenarios, which were used to quantify fuel consumption using the CWZ framework. The fuel use and emissions rates for the vehicles considered in this study when idle and at an increment of 10 mph speeds are presented in Table 1 and Table 2, respectively. For a pilot vehicle operation, fuel consumption and emission rates during idling conditions were calculated by using the idling fuel use values published by Argonne National Laboratory (2014).

Table 1. Idling fuel use and emission rate per vehicle type

Vehicle Type	Fuel Type	Idling Fuel Use (gal/hour)	Emission Rate ($kgCO_2$-e/veh-hour)
Passenger Car (PC)/Sport Utility Vehicle (SUV)	*Gasoline*	0.39	1.68
Light Duty Truck (LDT)	*Diesel*	0.44	5.28
Heavy Duty Truck (HDT)	*Diesel*	0.64	7.68

Table 2. Fuel use and emission rate per vehicle type under different speed ranges

	Fuel Use (gal/mile)			Emission Rate ($kgCO_2$-e/veh-mile)		
Speed	*PC/SUV (Gasoline)*	*LDT (Diesel)*	*HDT (Diesel)*	*PC/SUV (Gasoline)*	*LDT (Diesel)*	*HDT (Diesel)*
5 mph	0.1482	0.1714	0.3601	1.55	2.06	4.32
15 mph	0.0723	0.0887	0.1608	0.76	1.06	1.93
25 mph	0.0561	0.0707	0.1203	0.59	0.85	1.44
35 mph	0.0476	0.0592	0.0965	0.50	0.71	1.16
45 mph	0.0451	0.0551	0.0818	0.47	0.66	0.98
55 mph	0.0439	0.0534	0.0695	0.46	0.64	0.83
65 mph	0.0449	0.0541	0.0644	0.47	0.65	0.77
75 mph	0.0496	0.0582	0.0685	0.52	0.70	0.82

Source: Kim et al. 2022

The Microsoft Excel-based tools for urban, suburban, and rural cases (each case has its own Excel file) are available to download in the supplementary information of this report. The input data required to run the tools and the process for computing GW for different CWZ scenarios and conditions is available on Sheet 1 of each tool.

CASE STUDIES

The Microsoft Excel-based tools developed in this project are available in the supplementary information of this report and were used to compute these cases.

Three highway sections, Interstate 95 in Miami-Dade County (Florida), Interstate 80 in Sweetwater County (Wyoming), and US Highway 71 in Audubon County (Iowa), were selected to demonstrate the use of the CWZ framework. The location information, along with percent trucks, AADT, and lane information for each case is presented in Table 3. The hourly traffic distribution used in this study for the urban and suburban/rural sections is shown in Figure 2.

Table 3. Selected highway sections for the three cases

State	Route	County	Description	Traffic Pattern Type	AADT (Two-Way)	Percent Trucks	Lanes (Each Direction)
Florida	I-95	Miami-Dade	US 395 and Miami River	Urban	184,500	4	4
Wyoming	I-80	Sweetwater	I-80 West of Green River	Suburban	20,978	46	2
Iowa	US 71	Audubon	Junction Poplar St at North Junction County Road F24	Rural	2,050	15	1

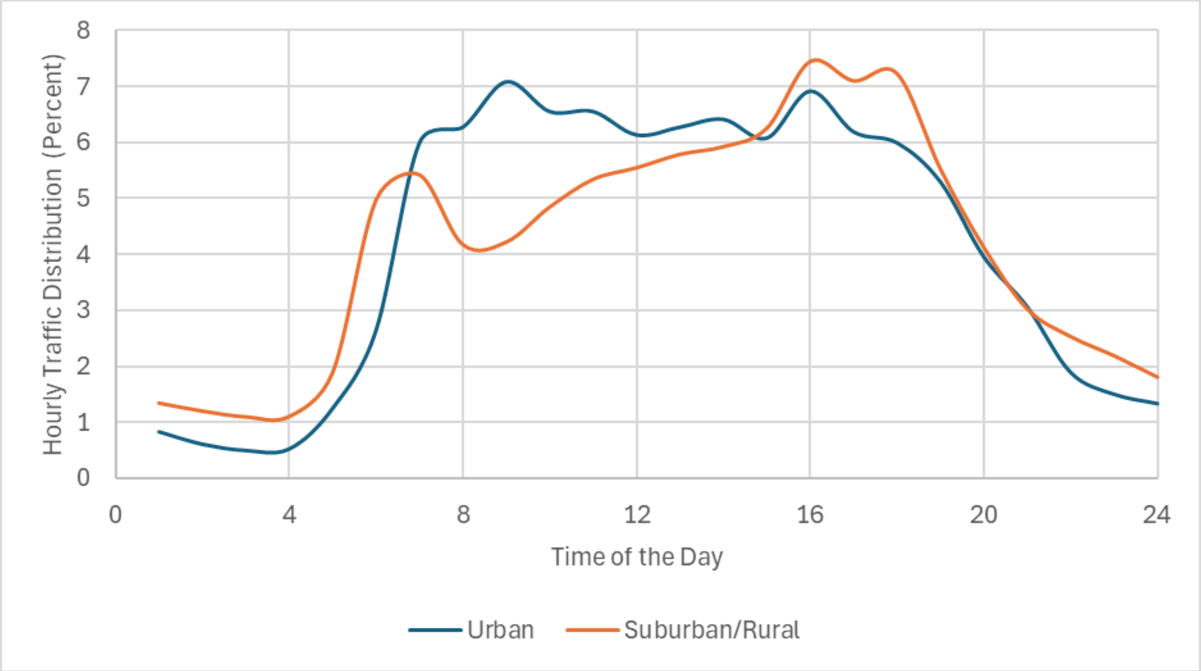

Figure 2. Hourly traffic distribution for urban and suburban/rural

A 1 mi closure is assumed for all of the cases with a maximum queue length of 10 mi. The traffic detouring is assumed to be 5% of the total traffic volume for all of the cases. It is also assumed that a 10 mph speed reduction occurs in all CWZ cases. The GW values for the combustion of gasoline and diesel from a life-cycle perspective (well-to-wheel) are 10.47 and 12.00 kg CO_2-e/gal. of fuel, respectively (National Renewable Energy Laboratories/USLCI 2019a, 2019b).

Urban Multilane Highway

A section of Interstate 95 between US 395 and the Miami River in Miami-Dade County (Florida) was selected as a case study of an urban multilane highway. The section had a two-way AADT of 184,500 with 4% truck traffic on four lanes in each direction (eight lanes total for both ways) (FDOT 2023). Table 4 shows the details of traffic operation conditions with and without traffic closure.

Table 4. Traffic operation conditions with and without traffic closures on multilane highway

Parameter	No CWZ	CWZ
Number of Lanes Open (One-Way)	4 lanes	2 lanes
Traffic Capacity	2,209 veh/lane	1,537 veh/lane
Speed Limit	65 mph	55 mph
Work Zone Length	-	1 mile
Maximum Queue Length	-	10 mile
Proportion of Detour Traffic Volume	-	5%

Using the Caltrans RealCost software (Caltrans 2013), it was found that with a 10-hour nighttime partial closure strategy, no traffic queue forms because the hourly traffic volume during nighttime does not exceed the highway capacity. Conversely, implementing a 24-hour continuous closure strategy resulted in a notably long traffic queue due to high hourly traffic volumes that surpassed the highway capacity during daytime hours, as shown in Table 5.

Table 5. Hourly traffic volume, capacity, and queued vehicles for the urban multilane highway case

24-Hour	10-Hour Nighttime Closure				24-Hour Continuous Closure			
	No. of Lanes Open to Traffic	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue	No. of Lanes Open to Traffic	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue
1	2	757	3,074	0	2	757	3,074	9,650
2	2	544	3,074	0	2	544	3,074	6,652
3	2	426	3,074	0	2	426	3,074	3,807
4	2	430	3,074	0	2	430	3,074	0
5	2	927	3,074	0	2	927	3,074	0
6	2	2,201	3,074	0	2	2,201	3,074	2,443
7	4	5,646	8,836	0	2	5,646	3,074	4,904
8	4	5,793	8,836	0	2	5,793	3,074	8,200
9	4	6,801	8,836	0	2	6,801	3,074	10,732
10	4	6,171	8,836	0	2	6,171	3,074	13,367
11	4	6,413	8,836	0	2	6,413	3,074	15,268
12	4	5,778	8,836	0	2	5,778	3,074	17,087
13	4	5,793	8,836	0	2	5,793	3,074	18,488
14	4	5,448	8,836	0	2	5,448	3,074	19,976
15	4	5,613	8,836	0	2	5,613	3,074	22,123
16	4	6,385	8,836	0	2	6,385	3,074	23,526
17	4	5,716	8,836	0	2	5,716	3,074	24,793
18	4	5,646	8,836	0	2	5,646	3,074	25,374
19	4	4,990	8,836	0	2	4,990	3,074	24,866
20	4	3,875	8,836	0	2	3,875	3,074	23,339
21	2	2,775	3,074	0	2	2,775	3,074	20,849
22	2	1,681	3,074	0	2	1,681	3,074	18,286
23	2	1,474	3,074	0	2	1,474	3,074	15,672
24	2	1,285	3,074	0	2	1,285	3,074	9,650

Suburban Multilane Highway

A section of Interstate 80 west of Green River in Sweetwater County (Wyoming) was selected as a case study of a suburban multilane highway. The two-way AADT for the section was found to be 20,978 with 46% truck traffic on two lanes in each direction (four lanes total for both ways) (State of Wyoming Legislature 2023). Table 6 shows the details of traffic operation conditions with and without traffic closure.

Table 6. Traffic operation conditions with and without traffic closures on multilane highway

Parameter	No CWZ	CWZ
Number of Lanes Open (One-Way)	2 lanes	1 lane
Traffic Capacity	1,575 veh/lane	822 veh/lane
Speed Limit	65 mph	55 mph
Work Zone Length	-	1 mile
Maximum Queue Length	-	10 mile
Proportion of Detour Traffic Volume	-	5%

Using the traffic models that are included in the Caltrans version of the RealCost software, it was found that a short traffic queue occurred during the early hours of the day (6:00 a.m. to 7:00 a.m.) with a 10-hour nighttime partial closure strategy, whereas implementing a 24-hour continuous closure strategy resulted in a long traffic queue due to high hourly traffic volumes that surpassed the highway capacity during daytime hours, as shown in Table 7.

Table 7. Hourly traffic volume, capacity, and queued vehicles for the suburban multilane highway case

24-Hour	10-Hour Nighttime Closure				24-Hour Continuous Closure			
	No. of Lanes Open	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue	No. of Lanes Open	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue
1	1	306	822	0	2	306	822	5,190
2	1	302	822	0	2	302	822	4,436
3	1	309	822	0	2	309	822	3,727
4	1	403	822	0	2	403	822	3,143
5	1	849	822	0	2	849	822	0
6	1	2,267	822	1,373	2	2,267	822	1,373
7	2	2,308	3,150	504	2	2,308	822	2,716
8	2	1,601	3,150	0	2	1,601	822	3,320
9	2	1,492	3,150	0	2	1,492	822	3,791
10	2	1,626	3,150	0	2	1,626	822	4,365
11	2	1,729	3,150	0	2	1,729	822	5,008
12	2	1,696	3,150	0	2	1,696	822	5,588
13	2	1,700	3,150	0	2	1,700	822	6,143
14	2	1,740	3,150	0	2	1,740	822	6,708
15	2	1,649	3,150	0	2	1,649	822	7,158
16	2	1,875	3,150	0	2	1,875	822	7,800
17	2	1,745	3,150	0	2	1,745	822	8,287
18	2	1,777	3,150	0	2	1,777	822	8,780
19	2	1,326	3,150	0	2	1,326	822	8,820
20	2	965	3,150	0	2	965	822	8,515
21	1	707	822	0	2	707	822	7,980
22	1	607	822	0	2	607	822	7,377
23	1	525	822	0	2	525	822	6,726
24	1	390	822	0	2	390	822	5,979

Rural Two-Lane Highway

A section of US Highway 71 between the junction at Poplar Street and the north junction at County Road F24 was selected as a case study of a two-lane highway in Iowa. The section had a two-way AADT of 2,050 with 15% truck traffic on one lane in each direction (two lanes total for both ways) (Iowa DOT 2020). Table 8 shows the details of traffic operation conditions with and without traffic closure.

Table 8. Traffic operation conditions with and without traffic closures on two-lane highway

Parameter	No CWZ	CWZ
Number of Lanes Open (One-Way)	1 lane	1 lane (Pilot Vehicle Operation)
Traffic Capacity	1,800 veh/lane	500 veh/lane
Speed Limit	45 mph	35 mph
Work Zone Length	-	1 mile
Maximum Queue Length	-	10 miles
Proportion of Detour Traffic Volume	-	5%
Pilot Vehicle Operation Cycle	-	240 secs
Effective Green Time	-	75 secs
Average Idling Time	-	82.5 secs

The fuel consumption calculation method was developed for a pilot vehicle operation on two-lane highways, which is different from multilane highways because Caltrans RealCost does not include the function for delay calculation under pilot vehicle operation. In such scenarios, traffic in both directions uses only one lane with the help of a pilot vehicle. Fuel consumption is mainly determined by the idle time in the queue while vehicles wait for a pilot vehicle to lead the traffic alternatively. Under a pilot vehicle operation, a traffic queue occurs at night (9:00 p.m. to 6:00 a.m.) for only a 10-hour nighttime closure, whereas implementing a 24-hour continuous closure strategy results in a traffic queue all day, as shown in Table 9.

Table 9. Hourly traffic volume, capacity, and queued vehicles for the rural two-lane highway case

Hour	10-Hour Nighttime Closure				24-Hour Continuous Closure			
	No. of Lanes Open	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue	No. of Lanes Open	Traffic Volume	Traffic Capacity	No. of Vehicles in Queue
1	1	10	500	10	1	10	500	10
2	1	6	500	6	1	6	500	6
3	1	5	500	5	1	5	500	5
4	1	5	500	5	1	5	500	5
5	1	6	500	6	1	6	500	6
6	1	11	500	11	1	11	500	11
7	1	18	1,800	0	1	18	500	18
8	1	28	1,800	0	1	28	500	28
9	1	43	1,800	0	1	43	500	43
10	1	61	1,800	0	1	61	500	61
11	1	74	1,800	0	1	74	500	74
12	1	82	1,800	0	1	82	500	82
13	1	82	1,800	0	1	82	500	82
14	1	81	1,800	0	1	81	500	81
15	1	81	1,800	0	1	81	500	81
16	1	81	1,800	0	1	81	500	81
17	1	78	1,800	0	1	78	500	78
18	1	71	1,800	0	1	71	500	71
19	1	59	1,800	0	1	59	500	59
20	1	47	1,800	0	1	47	500	47
21	1	37	500	37	1	37	500	37
22	1	28	500	28	1	28	500	28
23	1	20	500	20	1	20	500	20
24	1	12	500	12	1	12	500	12

RESULTS

Urban Multilane Highway

A GW of -89 kg CO_2-e per 10-hour nighttime closure and 3,389,783 kg CO_2-e per 24-hour continuous closure was observed for the urban case, as can be seen in Table 10. During nighttime closure of the urban highway section, the reduction in GW can be attributed to the decrease in vehicle speeds from 65 mph to 55 mph within the CWZ. As shown in Table 2, PC, SUV, and LDT are more fuel efficient at 55 mph. This is because at this speed, the vehicles' last gear is engaged, and as the speed is further increased, higher fuel consumption is expected due to increased air resistance (increasing at a rate of the velocity squared). Furthermore, no additional traffic delay due to lane closure was observed in the case of the nighttime closure because hourly traffic demands did not exceed the hourly traffic capacity. On the other hand, GW for the case of a 24-hour closure was significantly high, i.e., 3,389,783 kg CO_2-e. This is because the hourly traffic demands exceeded the reduced hourly traffic capacity, resulting in additional travel times and a longer waiting time in the CWZ queues.

In the case of a 24-hour continuous closure on a 1 mi CWZ with two lanes closed on a four-lane highway in one direction, the GW for an 8-hour work shift was computed to be as high as 48,439 metric tons CO_2-e, while for a 24-hour work shift the GW was determined to be 16,135 metric tons of CO_2-e. Due to no queue formation and slower speeds, the nighttime closure in the case of the CWZ resulted in reduced GW of 1,484 kg CO_2-e, indicating that driving at high gear but lower speeds results in efficient fuel consumption.

Table 10. GW by construction strategy for CWZs and detours

Road Type	Route/State	GW (kgCO$_2$-e/Closure)		Number of Closures Needed for 1 mi Construction			Total GW (kg CO$_2$-e/lane-mile)		
		Per 10-hour nighttime Closure	Per 24-hour Closure	No. of 10-hour Closures	No. of 24-hour Closure with 8-hour Work Shift	No. of 24-hour Closure with 24-hour Work Shift	10-hour Closure	24-hour Closure with 8-hour Work Shift	24-hour Closure with 24-hour Work Shift
Urban	I-95/Florida	-89	3,389,783	16.67	14.29	4.76	(1,484)	48,439,999	16,135,367
Suburban	I-80/Wyoming	27	203	16.67	14.29	4.76	450	2,901	966
Rural	US 71/Iowa	35	186	16.67	14.29	4.76	583	2,658	885

Suburban Multilane Highway

A GW of 27 kg CO_2-e per 10-hour nighttime lane closure and 203 kg CO_2-e per 24-hour continuous one-lane closure was observed for the suburban highway section with two lanes in each direction, as shown in Table 10. In the 10-hour nighttime closure scenario, the hourly traffic demands were found not to exceed the hourly traffic capacity except for two hours (5:00 a.m. to 7:00 a.m.), resulting in a low GW. However, the GW values for a 24-hour continuous closure with 24-hour work shift and 8-hour work shift scenarios in suburban conditions were found to be almost 6.5 times and 2 times higher compared to the 10-hour nighttime closure scenario because the hourly traffic demands exceeded the reduced hourly traffic capacity during the lane closure. The GW of one lane-mile of construction was computed to be 450, 2,901, and 966 kg CO_2-e per lane-mile for a 10-hour nighttime closure and 24-hour continuous one-lane closures with 8-hour and 24-hour work shifts, respectively.

Rural Two-Lane Highway

The GW values for a two-lane road in the rural case were determined to be 35 kg CO_2-e for a 10-hour nighttime closure with a pilot vehicle operation and 186 kg CO_2-e for a 24-hour continuous closure with a pilot vehicle operation as shown in Table 10. Although the hourly traffic demands did not exceed the hourly traffic capacity for either the 10-hour nighttime closure or the 24-hour continuous closure, vehicles experienced longer idling periods. This occurred because they had to wait for a pilot vehicle to escort them in each direction alternately during lane closures.

The resulting GW of vehicles idling in the pilot vehicle case was observed to be higher when compared with the GW caused by speed changes in the CWZs. The GW values of one lane-mile of construction were found to be 583, 2,658, and 885 kg CO_2-e for a 10-hour nighttime closure and 24-hour continuous one-lane closures with 8-hour and 24-hour work shifts, respectively, with pilot vehicle operation.

SUGGESTED DECISION SUPPORT FRAMEWORK

To decide which CWZ closure would be most beneficial in terms of lower GW, the AADT was systematically entered into the GW estimation tools from as low as 10,000 vehicles per day for multilane highways and 1,000 vehicles per day for two-lane highways. The GW increased as the AADT increased for one-lane closures and two-lane closures for multilane urban highways, 10-hour nighttime closures versus 24-hour continuous closures (8-hour and 24-hour work shifts) for multilane suburban highways and two-lane highways. Significant differences in GW were observed when hourly traffic demands exceeded hourly traffic capacity during morning and afternoon peak hours. As AADT continued to increase, the GW for the different cases and closure scenarios increased as well. Utilizing this information, a decision support framework was developed to identify optimal lane closure strategies for each case, aiming to minimize excessive GW in CWZs during construction activities that require lane closures. Figures 3 through 6 show the GW changes for one lane-mile of construction by lane closure duration and number of lanes closed in the CWZ. Note that this section demonstrates an example of how a decision support framework could be developed based on the user scenarios and local data.

Figure 3 shows the GW values for one lane-mile of construction for multilane highways in urban areas with 10-hour nighttime closures. The GW values did not show significant differences between one-lane closures and two-lane closures until the two-way AADT reached 240,000 vehicles per day, but the GW of the two-lane closures after 260,000 AADT increased significantly compared to the GW of the one-lane closures for 10-hour nighttime closures. According to these results, it could be concluded that when AADT exceeds 240,000 vehicles per day, one-lane closures should be chosen for 10-hour nighttime closures to avoid excessively high GW.

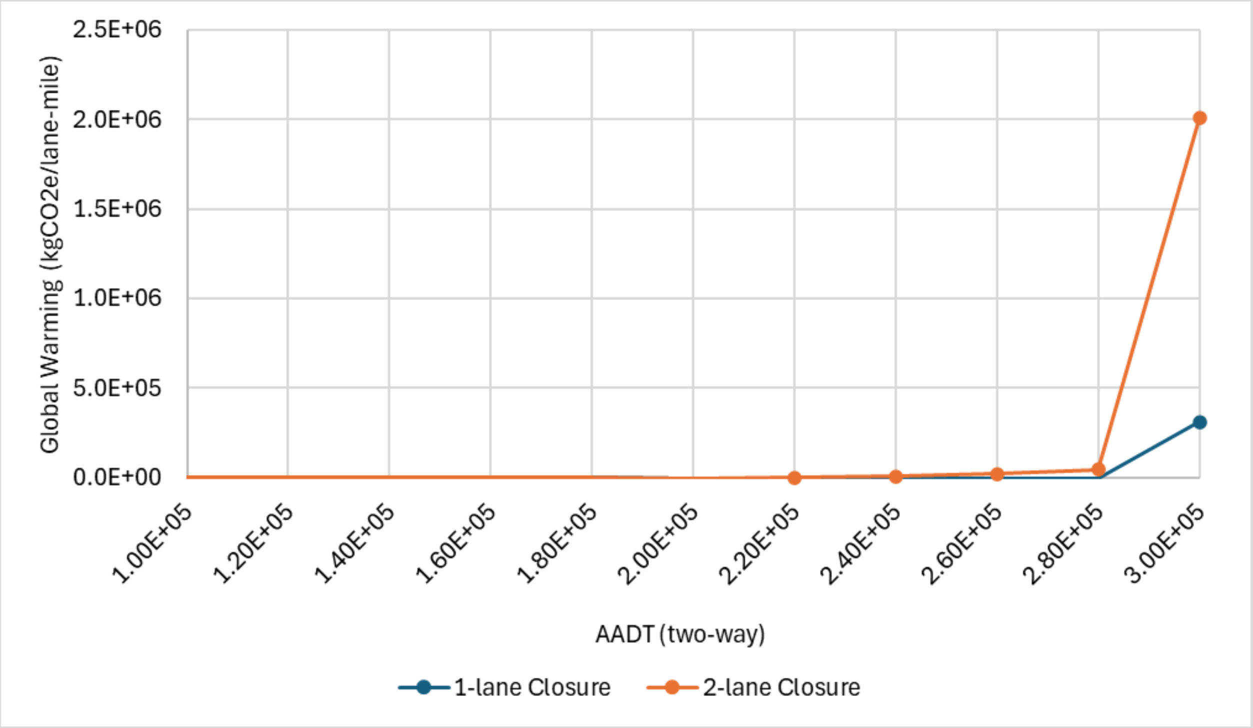

Figure 3. GW for one lane-mile of construction for urban multilane highways with 10-hour nighttime closures

Figure 4 shows the GW values for one lane-mile of construction for multilane highways in urban areas with 24-hour nighttime closures with 8-hour and 24-hour working shifts. The GW values do not show significant differences between one-lane closures and two-lane closures until the two-way AADT reached 100,000 vehicles per day. The GW of the two-lane closures after 100,000 AADT increased significantly compared to the GW of the one-lane closures in the 24-hour continuous closure scenario, whether it was the 8-hour or 24-hour work shift. Thus, it can be concluded that when the AADT exceeds 100,000 vehicles per day, one-lane closures should be chosen for 24-hour continuous closures to avoid excessively high GW. Within the 24-hour continuous one-lane closure, a higher number of working shifts, such as three work shifts in a 24-hour period compared to a single 8-hour work shift, would result in lower GW due to the CWZ.

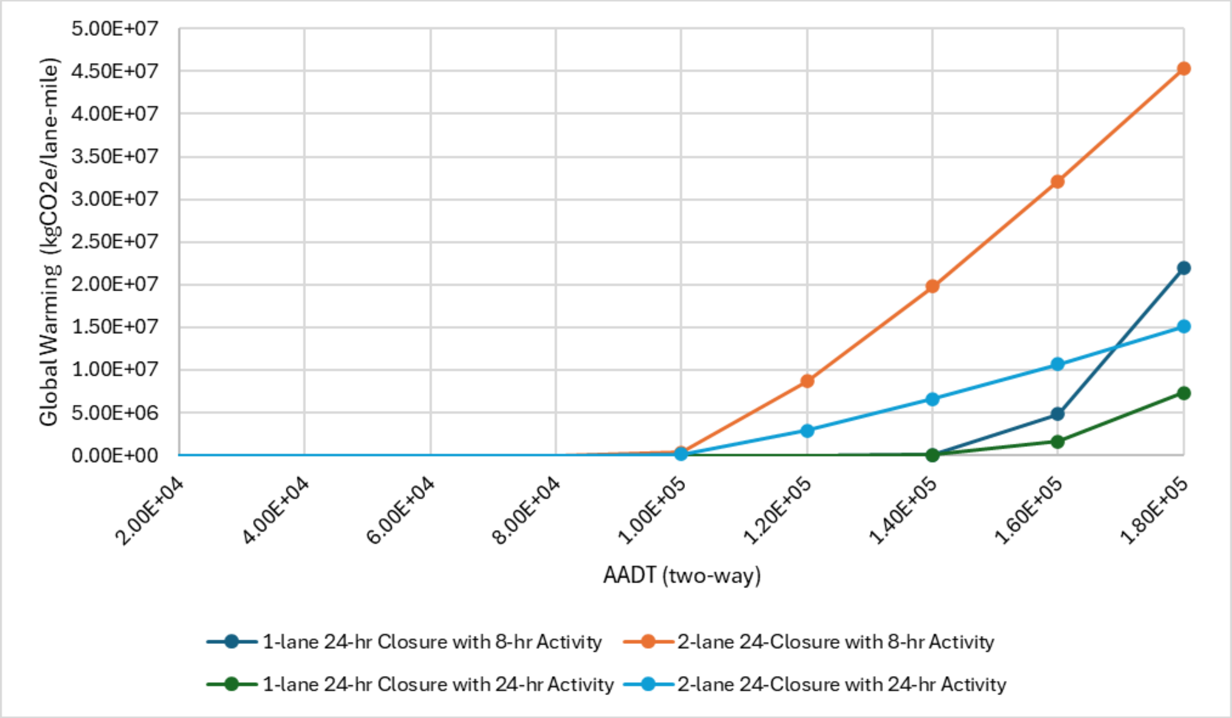

Figure 4. GW for one lane-mile of construction for urban multilane highways with 24-hour continuous closures

Figure 5 shows the GW values for one lane-mile of construction for a multilane highway case in a suburban area with 10-hour nighttime closures and 24-hour continuous closures. The GW values did not show significant differences between 10-hour nighttime closures and 24-hour nighttime closures in one-lane closures until the two-way AADT reached 30,000 vehicles per day, but the GW of the 24-hour continuous closures with an 8-hour work shift after 40,000 AADT increased significantly compared to the 10-hour nighttime closures. According to the results, when AADT exceeds 40,000 vehicles per day, 10-hour nighttime closures should be chosen to avoid high GW. The results also show that a 24-hour work shift in a 24-hour continuous closure has a lower GW compared to an 8-hour work shift. However, it was still found to be higher when compared with a 10-hour nighttime closure scenario.

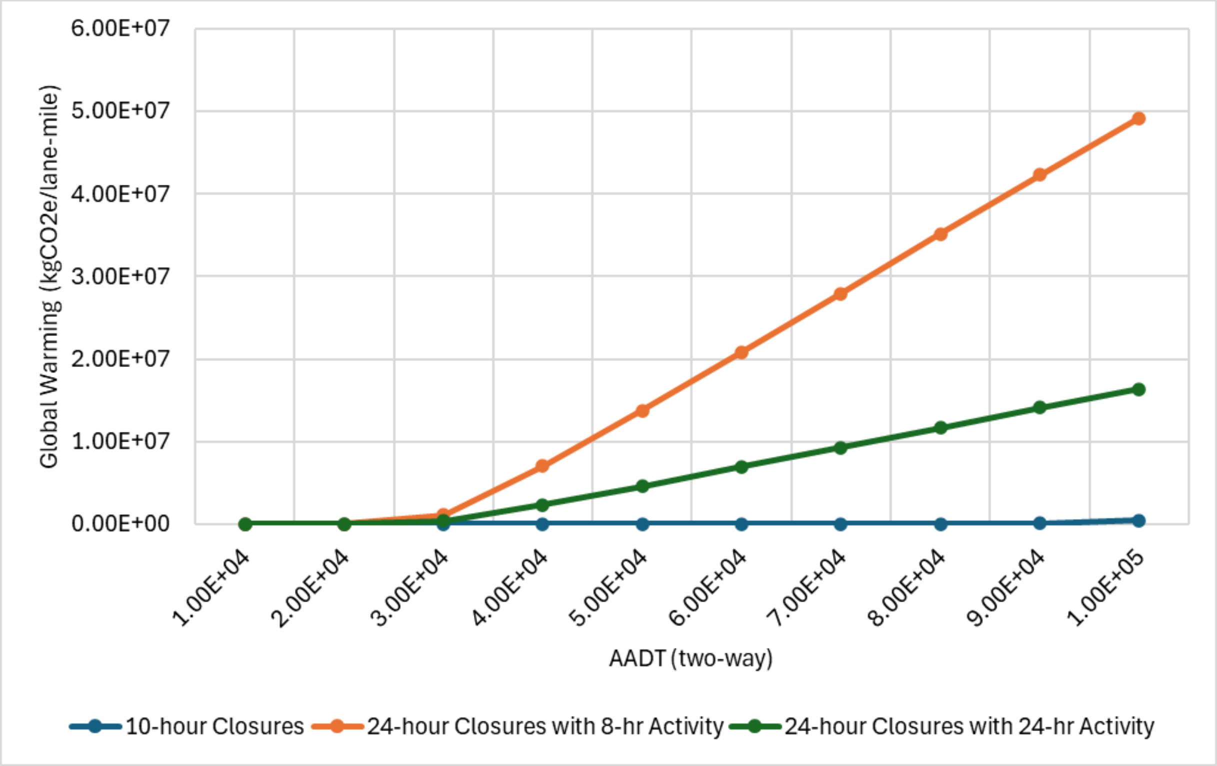

Figure 5. Global warming for one lane-mile of construction for suburban multilane highways

Figure 6 shows the GW values for one lane-mile of construction for two-lane highways in rural areas with 10-hour nighttime closures and 24-hour continuous closures. The GW values show the differences between 10-hour nighttime closures and 24-hour closures with one-lane closures from 1,000 AADT, and the difference in GW between them increases as the AADT increases. According to the results, 10-hour nighttime closures should be chosen when available to avoid excessively high GW compared with 24-hour continuous closures with only an 8-hour work shift, regardless of AADT level. Note that the 24-hour continuous closure with a 24-hour work shift showed similar GW to that of 10-hour nighttime closure around 1,000 two-way AADT. However, as the two-way AADT increased, the difference in the GW between the two scenarios increased by a relatively small amount.

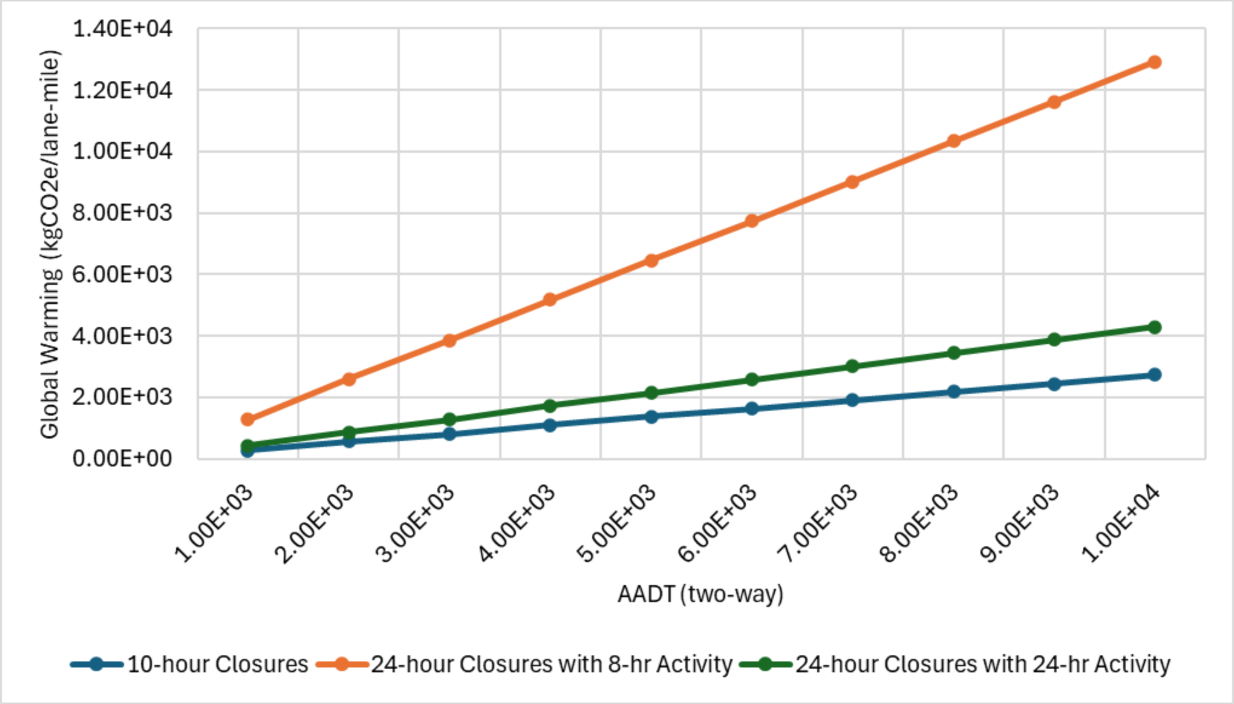

Figure 6. GW for one lane-mile of construction for rural two-lane highways

Figure 7 illustrates the lane closure strategy that can be adopted and the decision support framework based on the cases and scenarios discussed. For multilane highways in urban areas, 10-hour nighttime closures should be chosen when the two-way AADT is greater than or equal to 100,000 vehicles per day, and one-lane closures should be chosen when the two-way AADT is greater than or equal to 280,000 vehicles per day. This minimizes GW during the lane closures in CWZs.

For multilane highways in suburban areas, 10-hour nighttime closures should be chosen when the two-way AADT is greater than or equal to 40,000 vehicles per day, and for two-lane highways in suburban areas, 10-hour nighttime closures should be chosen when available regardless of AADT.

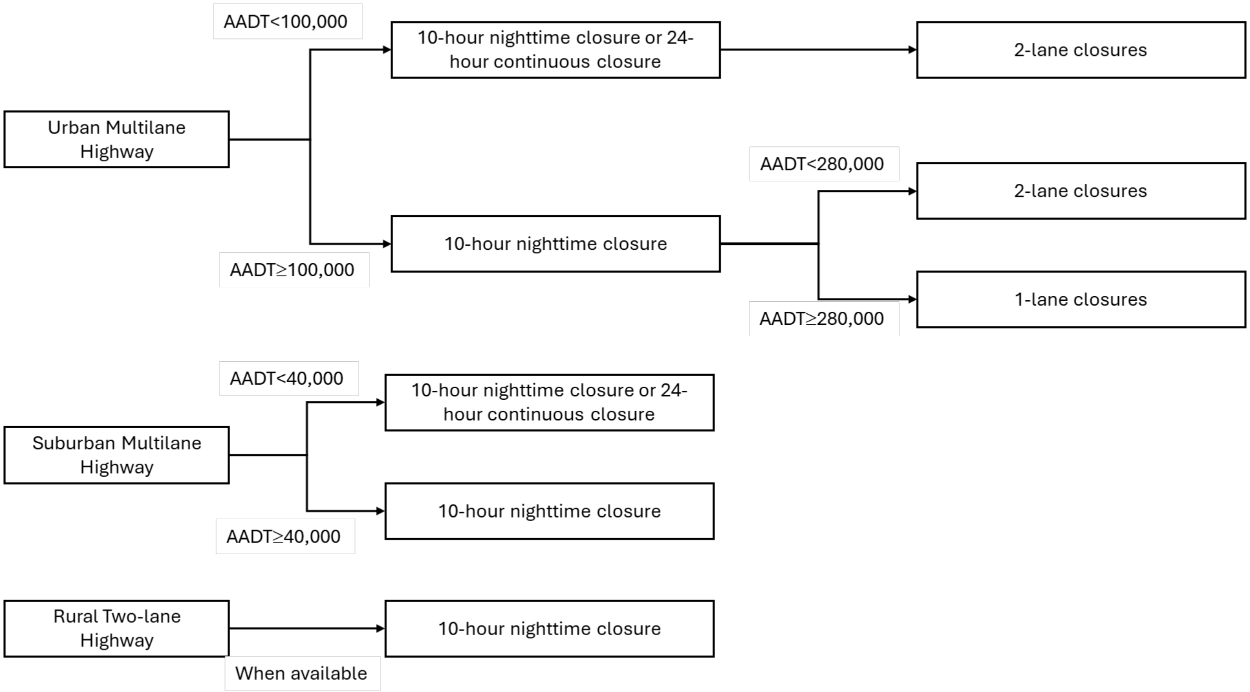

Figure 7. Lane closure strategy decision-making framework

CWZ SAFETY ASPECT

CWZs often cause inconvenience for road users. Temporary lane configurations and other work-related environments within CWZs often lead to traffic accidents. According to the National Safety Council, work zone accidents in 2022 resulted in 891 fatalities and 37,701 injuries (NSC 2024). Of the 891 deaths, 742 (83%) involved motor vehicle drivers and passengers. According to FHWA, one fatality occurs every 4 billion vehicle miles traveled (VMT; which equals 2.5e-10 fatalities per VMT) exposed to CWZs and every $112 million in road construction costs (FHWA 2024).

Arditi et al. (2007) examined the accident characteristics of nighttime and daytime highway CWZs and found that nighttime construction had a fivefold higher fatality rate compared to daytime construction. Zhang and Hassan (2019) conducted a crash severity analysis for nighttime and daytime highway work zones, concluding that significant differences exist between the factors influencing injury severity in work zone crashes during these periods. Their study also identified trends, such as an increased fatality rate in rainy conditions and heightened injury severity during nighttime crashes associated with speeding.

As this study focuses on traffic delays rather than construction costs, the CWZ fatality indicator was adapted from FHWA data (FHWA 2024), a daytime factor of 2.5e-10 fatalities per VMT in a CWZ. For the nighttime closures, the CWZ fatality indicator was adjusted by a multiplier of 5.0, based on findings from Arditi et al. (2007). Hence, the nighttime factor computes to be 1.25e-9 fatalities per VMT. For 24-hour continuous closures, the average of the daytime and nighttime factors computes to be 7.5e-10 fatalities per VMT. Multiplying the VMT for each case study, the fatality indicator could be determined and compared for daytime, nighttime, and 24-hour continuous closure scenarios, as shown in equations 1 through 3.

$$\text{CWZ fatality indicator (daytime)} = 2.5\text{e-}10 \times (\text{VMT in CWZ}) \tag{1}$$

$$\text{CWZ fatality indicator (nighttime)} = 1.25\text{e-}9 \times (\text{VMT in CWZ}) \tag{2}$$

$$\text{CWZ fatality indicator (24-hour)} = 7.5\text{e-}10 \times (\text{VMT in CWZ}) \tag{3}$$

The CWZ fatality indicator could be considered a reflection of the relative risk of fatalities in CWZs rather than the absolute number of fatalities. This is because the indicator is based on only one data source, which changes every year. The CWZ fatality indicator was calculated for the three different cases discussed in this study, and the results are shown in Table 11.

Table 11. CWZ fatality indicator based on the three case studies

Case Type	Closure Type	Number of Closures Needed for One Lane-Mile of Construction	CWZ Fatality Indicator (1e-4)
Urban Multilane Highway	10-hour Nighttime Closure	16.67	2.60
	24-hour Continuous Closure with 8-hour Work Shift	14.29	9.92
	24-hour Continuous Closure with 24-hour Work Shift	4.76	3.30
Suburban Multilane Highway	10-hour Nighttime Closure	16.67	1.39
	24-hour Continuous Closure with 8-hour Work Shift	14.29	3.20
	24-hour Continuous Closure with 24-hour Work Shift	4.76	1.07
Rural Two-Lane Highway	10-hour Nighttime Closure	16.67	0.03
	24-hour Continuous Closure with 8-hour Work Shift	14.29	0.11
	24-hour Continuous Closure with 24-hour Work Shift	4.76	0.04

The CWZ fatality indicator varies by AADT, number of closures, length of CWZ, and closure type. For one lane-mile of construction on an urban multilane highway section (Case 1), the CWZ fatality indicators for 24-hour continuous closures with 8-hour and 24-hour work shifts were 3.8 and 1.3 times higher than the CWZ fatality indicator for 10-hour nighttime closures, respectively. For one lane-mile of construction on a suburban multilane highway section (Case 2), the CWZ fatality indicators for 24-hour continuous closures with 8-hour and 24-hour work shifts were 2.3 times higher and 0.8 times lower than the CWZ fatality indicator for 10-hour nighttime closures, respectively. Lastly, for one lane-mile of construction on a rural two-lane highway section, the CWZ fatality indicator for 24-hour continuous closures with 8-hour and 24-hour work shifts were 3.7 and 1.3 times higher than the CWZ fatality indicator for 10-hour nighttime closures, respectively. Regardless of highway case, the CWZ fatality indicators for 24-hour closures with 8-hour work shifts were two to five times higher than the CWZ fatality indicators for 10-hour nighttime closures due to the increased vehicle exposure on CWZs during 24-hour continuous closures with 8-hour work shifts.

CONCLUSIONS

This study demonstrates the GW for different cases (urban, suburban, and rural) in different CWZ closure scenarios (10-hour nighttime, 24-hour continuous [8- and 24-hour work shifts], and pilot vehicle operation) under different traffic conditions. The cradle-to-lay environmental impacts of rigid pavement construction are not computed in this study. As expected, it was observed that daytime closures such as the 24-hour continuous closures in any considered scenario (8- or 24-hour work shifts; urban, suburban, and rural settings) significantly contribute to the GW per closure. This is mainly due to high traffic volumes, traffic congestion, and long CWZ queues during the daytime rush hours, i.e., morning and afternoon commute when many people are driving to and from work, respectively. However, the greater productivity of working 24-hour instead of 8-hour work shifts in a 24-hour continuous closure significantly reduces the GW results. In many cases, the 24-hour continuous closure with 24 hours of work per day does not reduce the GW to that of the 10-hour closures.

A positive impact, reflected as a reduction in GW, was observed when daytime closures and CWZs were avoided in urban areas and instead 10-hour nighttime closures were used. This outcome is attributed to more fuel-efficient driving speeds. The suburban and rural settings showed similar GW impacts for the closure types considered in this study; a slightly increased GW in the rural setting compared to the suburban setting was observed for the 10-hour nighttime closure. This is because of the freight transport by trucks in the pilot vehicle operations in rural settings, which results in idle fuel consumption as vehicles must wait in a queue before the pilot vehicle moves traffic from one side of the CWZ to the other. Due to higher productivity rates with 24-hour work shifts compared to 8-hour work shifts in a 24-hour continuous closure, significant GW reduction was seen in all three road type settings.

A decision support framework was also developed for the limited number of cases analyzed in this paper to help determine when or at what AADT each type of closure is preferable for urban, suburban, and rural settings. This framework is applicable to the scenarios and data used in this study and therefore should not be generalized and should be augmented with more detailed results to cover the full range of possible cases. This framework also does not consider the changes in concrete materials needed for 10-hour closures compared with 24-hour continuous closures. Typically, the concrete mixes for 10-hour closures require much shorter times to reach strengths that enable them to be opened to traffic, which in many cases will result in mix designs that have higher GW than mixes used for 24-hour continuous closures. This consideration should be included in future development of the framework.

Based on the study results, it can be concluded that 10-hour nighttime closures resulted in lower GW in many cases, and the GW tradeoffs of using 10-hour closures versus 24-hour continuous closures should be considered especially where the GW differences are largest. In particular, 24-hour continuous closures with only an 8-hour work shift should only be used where absolutely necessary. Continuous 24-hour closures with continuous 24-hour work shifts are much more competitive with 10-hour nighttime closures in terms of GW in suburban and rural settings. A 24-hour continuous closure should primarily be considered if there are any practical operational hurdles, if nighttime closures are not possible, and if traffic on that route is low (AADT <

100,000 for urban settings and AADT < 40,000 for suburban settings). Additionally, 24-hour work shifts reduce the number of closures, resulting in reduced GW in 24-hour continuous closure scenarios. However, 10-hour nighttime closures still resulted in the least GW in all considered cases. Note that 10-hour nighttime closures have the longest construction durations and often cost the most money because of the inefficiencies of frequent mobilization and demobilization.

It should also be noted that any differences in accident rates between different closure types should be identified and considered in decision making. The CWZ fatality indicator calculator showed that 24-hour closures with 24 hours of continuous work were about as safe as 10-hour nighttime closures, which should be considered in decision support.

The Microsoft Excel-based tools for urban, suburban, and rural conditions were developed to perform the case studies in this project and are made available in the supplementary information with this report. Agencies can use their local data as input with these tools to compute the GW values that arise from the CWZ scenarios in their regions. Note that the tool provides users the ability to input the number of lane closures during any hour of the day instead of selecting 10-hour nighttime or 24-hour continuous closures. Also note that the CWZ GW calculations are based on one day of activity. Users must scale the CWZ GW results to the number of construction days/number of needed closures and should particularly note that 24-hour closures with continuous work (24 hours of work per 24 hours of closure) significantly shorten the overall amount of time needed to complete the project. The shared simple GW calculation tools can help agencies quantify GW rather quickly and make well-informed decisions.

Other efforts that could help reduce GHG emissions from CWZs include using cleaner/renewable fuels, optimizing transportation routes to reduce fuel use, adopting energy-efficient practices on construction sites, reducing the frequency of maintenance cycles, avoiding long daytime closures especially during rush hours, and promoting sustainable construction materials and practices.

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APPENDIX. SUPPLEMENTARY MATERIALS

The Microsoft Excel files developed for the three cases presented in this study are available with this report at the links below. The instructions to input data and run the analyses are included in the first sheet of each file.

1. Multilane Urban Road – Traffic and Emission Calculation
2. Multilane Suburban Road – Traffic and Emission Calculation
3. Two-Lane Rural Road – Traffic and Emission Calculation

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