ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSION FROM HIGHWAY WORK ZONE TRAFFIC IN PAVEMENT LIFE CYCLE ASSESSMENT

Ting Wang[1], Changmo Kim[2]* and John Harvey[2]

[1] AgileAssets Inc. 3001 Bee Caves Rd Ste 200, Austin, TX 78746
[2] University of California Pavement Research Center, Dept. Civil and Environmental Engineering, UC Davis, 1 Shields Ave, Davis CA, 95616

* Corresponding author: chkim@ucdavis.edu

ABSTRACT

This study built a model to characterize traffic conditions in the highway work zones to examine the environmental impacts from work zone traffic delays and their relative significance compared with other processes in the pavement life cycle, including material production, construction and use phases. The demand-capacity model in the Highway Capacity Manual that has been extended to calculate work zone traffic delays was adopted for the traffic model in this study. The key inputs of the work zone traffic model include the daily traffic volume, hourly traffic distribution, highway configuration, and lane closure strategy. The key outputs of the model include the average queue length and speed, which used to calculate energy consumption and greenhouse gas (GHG) emissions using the *MOVES*. The model was then applied to four case studies analyzed in a previous pavement LCA study to assess the impacts of the work zone traffic. Using the system definitions of the four case studies with different scenarios for lane closure strategy, it was found that the energy consumption and GHG emissions caused by the work zone traffic were very small relative to other processes in the life cycle in rural areas, even when considering extreme closure tactics. Therefore, the assumption in the previous study that the impacts from work zone traffic are negligible is valid. It was also found that when no queue develops, there can be little energy savings and GHG emission reductions due to the reduced speed limit in the work zone.

INTRODUCTION

In a previous study *(1)* it was demonstrated that the volume of traffic on a road segment plays the most important role in determining whether there will be a net reduction or increase in life cycle energy and GHG emissions as a result of performing a maintenance treatment on a pavement. The analysis in that study assumed that the lane closures for construction occur during 9-hour nighttime periods and there is very small traffic delay. Therefore, the energy consumption and GHG emissions from the work zone traffic was small enough to be neglected from the analysis. In the study presented in this paper, this assumption was addressed by developing a model to determine the environmental impacts from the work zone traffic in terms of energy consumption and GHG emissions. This model can be applied to analyze any work zone traffic and can be integrated into any life cycle assessment (LCA) model for pavement rehabilitation or maintenance construction.

A work zone is defined in the Highway Capacity Manual (HCM) as a segment of highway where maintenance and construction operations impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the area *(2)*. Depending on the extent of the construction work and the traffic volume on the affected segment, the impact of the work zone on traffic can vary from insignificant for minor work zone restrictions on low-volume roads to highly significant for major lane closures on high-volume highways.

In pavement LCA, the impact of work zones is focused on the difference in traffic flow between the normal condition where no construction happens (i.e., a *Do Nothing* scenario), and the scenarios where a construction event is occurring. During the construction event, one or more lanes on the highway segment needs to be closed and the traffic capacity of this segment is reduced. Therefore it is possible that during the construction period, the traffic demand may exceed the capacity of the road resulting in development of a queue. The vehicles in the queue can therefore experience significant stop-and-go traffic conditions (Level-of-service F) which would be expected to increase energy consumption compared to more steady speed flow, and also increase GHG emissions. Posted speed limits in work zones are usually lower than the normal speed limit on that segment, which can also change the fuel economy of the vehicles passing through the work zone.

Previous studies have used two methods to address the impacts from work zone traffic for pavement LCA:

1. Use the demand-capacity (D-C) model as described in the HCM to characterize the work zone traffic and acquire the properties of the work zone traffic flow, such as average queue speed and average queue length *(3)*. Then apply a vehicle emission model to calculate the emissions based on the output of the demand-capacity model.
2. Use a microscopic traffic simulation model to characterize the work zone traffic *(4)*. In addition to the average queue speed and queue length, the microscopic model is able to generate the instantaneous speed of individual vehicles that pass through the work zone. Then a vehicle emission model is applied, based on the outputs of the microscopic traffic model, to calculate the GHG emissions.

The D-C model is suitable for quick implementation with simple input components: hourly traffic volumes, capacity, and the lane closure scheme. The Federal Highway Administration (FHWA) has developed the computational procedures to assess the road user cost of work zone traffic delay, using the D-C model, in life cycle cost analysis (LCCA) *(5)*. Although the accuracy of the result may be compromised by adopting the D-C model and the average queuing speed, modern vehicle emission models are able to address the vehicle emission using only average speed, taking into consideration the possible speed fluctuation that the vehicle may experience based on the facility type, such as highways and streets.

Although a microscopic traffic simulation generates disaggregated traffic data for the work zone, the use of this approach adds a great deal of complexity to pavement LCA model, and traffic simulation tools are commercial software which increase the cost of analysis. Furthermore, using a microscopic traffic simulation model to characterize the work zone traffic demands intensive work and often difficult to obtain input data for computation and calibration, especially for high traffic volume facilities. Although individual vehicles in the work zone traffic can be analyzed, using microscopic traffic simulation may not significantly increase the accuracy of the result *(5)*, and, as the case studies presented later in this paper show, the work zone traffic is relatively insignificant in the final result. Therefore, considering the significant advantage in time and resources needed to implement the D-C model compared with microscopic traffic simulation, using the D-C model to characterize the work zone traffic is chosen as the method in this study.

METHODOLOGY

Basic Concepts of Work Zone Traffic

Before detailing the procedures of characterizing the work zone traffic and the energy consumption and emissions, this section introduces basic concepts of work zone traffic and provides a detailed explanation of the method used to calculate energy consumption and GHG emissions from for the work zone traffic.

Work Zone Environmental Impacts

Pavement LCA can be used to examine the life cycle differences in environmental impacts between the construction scenario and the *Do Nothing* scenario. This study focused on the energy consumption and GHG emissions, but the approach can be applied to include other impact categories using mid-point indicators. It should be noted that even under the *Do Nothing* scenario, a D-C model may predict that a queue develops during the peak hours of the day when demand exceeds capacity. In either situation, the work zone environmental impacts are calculated as the difference between doing the construction and the *Do Nothing* scenario.

Work Zone Traffic

The work zone is an area of a highway where a construction event is occurring that reduces the number of lanes available to traffic or changes the operating rules, such as speed limits. In this study, the work zone traffic components include the upstream traffic, queuing zone, and the reduced speed zone, as shown in Figure 1.

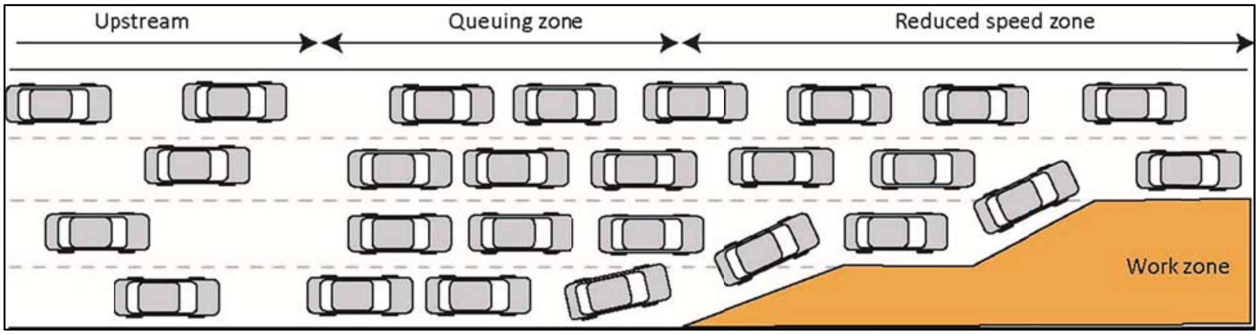

Figure 1: Components of work zone traffic.

Upstream traffic is the traffic flow that is not affected by the work zone, which is considered the same between the construction scenario and the *Do Nothing* scenario, and is not included in the analysis. The reduced speed zone is the area where vehicles are travelling at the work zone posted speed limit. Typically, no queue develops in this area. However, because the posted speed limit in a work zone is usually lower than the normal speed limit on the same segment, it is possible that vehicles travelling in this area have lower energy consumption and emissions compared with the *Do Nothing* scenario. This study used 55 mph (89 km/h) as the work zone posted speed limit for the freeway segments and 45 mph (72 km/h) as the work zone posted speed limit for highway segments.

Depending on the number of lanes that are open, a queue may develop when hourly traffic demand exceeds the work zone capacity. Once a queue develops, all approaching vehicles from the upstream traffic flow must slow down to the queuing speed and travel through the length of the physical queue under forced-flow conditions. As long as demand exceeds capacity, the length of the queue grows. When the demand eventually falls below capacity, or when capacity is increased above demand by removing the work zone restriction, vehicles then leave the queue faster than they arrive and the length of the queue shrinks and eventually dissipates. The vehicles in the queue can experience frequent stop-and-go driving conditions and can substantially increase the energy consumption and GHG emissions compared to a possible free-flow situation. The LCCA manual from the U.S. FHWA uses Level-of-Service (LOS) F to characterize the traffic flow in the queuing zone. The detailed procedure to calculate the queuing speed and queue length are described in the next section.

Hourly Traffic Distribution

Traffic level analysis in the D-C model is performed on an hourly basis. Therefore, the hourly traffic is an essential input because it is the base for comparisons between the demand on the road segment and the ability to carry that traffic through the work zone. Hourly traffic distribution represents the portion of daily traffic in each hour. In this study, the hourly traffic distribution was acquired from the California Department of Transportation (Caltrans) Performance Measurement System (*PeMS*) *(6)*. *PeMS* uses electronic detectors to measure the speed and traffic count on a number of segments in the state highway network. The database includes both historical and real-time data on the California highway system. For each *PeMS* station, hourly traffic distributions for weekdays and weekends were generated separately to address the difference due to the travel purposes (commuting vs. non-commuting travels). To ensure that any specific roadway segment has an hourly distribution even though it does not have a *PeMS* station, the distributions from all *PeMS* stations were also aggregated to produce typical values for rural and urban highways. In the model, if a roadway segment has a *PeMS* station, the hourly distribution factor from the corresponding station is used. Otherwise a value is selected, based on the county and road type (rural or urban).

Analysis Procedure

The computational analysis procedure is based on the HCM and the calculation of user delay cost in the LCCA procedure *(7)*. Once the work zone traffic is addressed, the *MOVES* model, developed by U.S. Environmental Protection Agency (EPA), is used to address energy consumption and GHG emissions *(8)*. The six overall steps are detailed as follows, and are used for both the construction scenario and the *Do Nothing* scenario to calculate the difference in energy consumption and GHG emissions.

1. Calculate the projected traffic demand in the construction year.
2. Calculate directional hourly traffic demand during construction.
3. Determine roadway capacities during normal operation and during construction.
4. Identify the work zone components (i.e., upstream traffic, queuing zone and reduced speed zone).
5. Quantify the traffic affected in each component.
6. Prepare the *MOVES* inputs based on the traffic quantified in the previous steps and run *MOVES* to calculate the energy consumption and GHG emissions.

Step 1. Calculate the Projected Traffic Demand in the Construction Year

The calculation of the projected traffic demand in the year when the construction event will be in place is based on the annual average daily traffic (AADT) of the current (base) year. This can be calculated based on the total traffic volume or each type of vehicle, using an average traffic growth rate, following Eq. (1):

$$\begin{aligned} FutureYear\ AADT = {} & BaseYear\ AADT \times ShowUp\% \\ & \times Vehicle\,Class\% \times \left(1 + GrowthRate\right)^{(FutureYear - BaseYear)} \end{aligned} \tag{1}$$

Where:

FutureYear AADT is the AADT in the construction year, *BaseYear AADT* is the AADT in the base year, *ShowUp*% is the portion of traffic that chooses to use the route, with other traffic choosing another route or transportation mode, *VehicleClass*% is the portion of vehicle type in the total vehicle population, and *GrowthRate* is the average annual traffic growth rate for that particular vehicle type.

Step 2. Calculate Work Zone Directional Hourly Traffic Demand

The directional hourly traffic demand is calculated from the *PeMS* database which was prepared as part of a previous pavement LCA study *(1)*. The directional hourly traffic distribution is a table including the portion of traffic in each of the 24 hours, with separate tables for weekdays and weekends.

Step 3. Determine Roadway Traffic Capacity

The following traffic capacities are calculated: 1) the capacity of the road under normal operating conditions (*normal capacity*); and 2) the *work zone capacity* during construction.

According to the HCM 2010, the maximum *normal capacity* for a multi-lane freeway is 2,400 passenger cars per hour per lane (pcphpl) *(2, Page 3-14)*, which may be reduced depending on the interchange spacing and number of lanes. According to the HCM 2010, the base capacity for a short-term freeway work zone is 1,600 pcphpl regardless of lane closure configuration *(2, Page 10-26)*. When comparing the capacity with the hourly demand to determine if a queue develops, the capacity in units of “passenger cars per hour per lane” needs to be converted to “vehicles per hour per lane” for the consideration of the influence of heavy vehicles. Eq.(2) shows the equations to calculate the adjusted capacity.

$$AdjustedCapacity = BaseCapacity \times \frac{1}{1 + P_T\left(E_T - 1\right)} \tag{2}$$

Where:

AdjustedCapacity	is the capacity adjusted for the heavy vehicles in units of vehicles per hour per lane
BaseCapacity	is base capacity for the segment in units of passenger cars per hour per lane
P_T	is the percentage of heavy vehicles in the total traffic flow
E_T	is the passenger-car equivalent for heavy vehicles, which is 1.5 for level terrain, 2.5 for rolling terrain, and 4.5 for mountain terrain *(2)*.

Step 4. Identify the Work Zone Components

With the roadway capacities established, the fourth step is to compare the roadway capacity with the hourly demand for the facility for the construction project. The fundamental principles are: 1) when there is a lane closure, the vehicles obey the posted reduced work zone speed limit. It is assumed that there is no queue in the work zone because the discharging flow rate downstream is higher than the flow rate in the work zone. 2) When the hourly demand exceeds the work zone capacity, the queue develops and continues to lengthen; and 3) when the capacity exceeds the hourly demand, any queue that has developed dissipates according to the difference between the demand and the capacity. If there is no queue, the only component is the reduced speed zone.

Step 5. Quantify the Traffic in each Component

In this step, the queue speed, average number of vehicles in the queue, and average queue length are calculated.

Queue Speed

Queue speed refers to the average speed of vehicles that travel in the queue. The speed through the queue can be determined by using the forced-flow average speed versus volume to capacity (V/C) ratio graphs for LOS F contained in an National Cooperative Highway Research Program (NCHRP) study *(9)*. A regression equation using the data from the figure is shown in Eq.(3).

$$Average\ queue\ speed\left(mph\right) = 13.33 \times \left(V/C \right)^2 + 11.42 \times \left(V/C \right) + 0.5 \tag{3}$$

Using the volume through the queue and the free-flow capacity of the road, the V/C can be calculated for each hour when the demands exceeds the capacity and used to find the corresponding speed. In this process, because traffic only exits the queue through the work zone, the volume through the queuing zone is limited to the capacity of the reduced speed zone, which is calculated in Step 3. The capacity in the queuing zone is the normal free flow capacity of this segment because there is no lane closed in this area.

Average Number of Vehicles in the Queue and Average Queue Length

The average number of queued vehicles in each hour is converted to average hourly queue lengths by dividing the average hourly number of queued vehicles by the change in traffic density between the upstream free-flow section and the queue section during that hour. The average number of queued vehicles can be calculated by taking the arithmetic average number of queued vehicles at the beginning and end of each hour. At the end of each hour, the numbers of the queued vehicles are added to the traffic demand in the next hour.

Traffic density is the number of vehicles on a mile of roadway (vehicles/mile). It can be calculated by dividing traffic flow through the section (vehicles per hour) by the average speed through the section. The upstream volume is the traffic demand in each hour, and the upstream speed is the normal speed limit for that segment. The queue volume is the work zone capacity because the traffic flow in the queue is restricted to the work zone capacity, and the queue speed is calculated in the previous step. Eq.(4) and Eq.(5) are the formulae for this step.

$$Average\ hourly\ queue\ length = \frac{Average\ number\ of\ queued\ vehicles\ during\ the\ hour}{Change\ in\ traffic\ density} \tag{4}$$

$$Change\ in\ traffic\ density = \frac{Queue\ volume}{Queue\ speed} - \frac{Upstream\ volume}{Upstream\ speed} \tag{5}$$

Step 6. Prepare the *MOVES* Inputs based on the Traffic Quantified in the Previous Steps and run *MOVES* to Calculate the Energy Consumption and GHG Emissions

The first five steps produce all work zone properties that are needed to characterize work zone traffic in *MOVES.* In the sixth step, all these inputs are converted to *MOVES* input files to calculate the energy consumption and GHG emissions.

In each *MOVES* scenario for a project, at least one of two cases is modeled: a weekday traffic condition and a weekend traffic condition depending on the construction strategy. Weekdays and weekends have different hourly traffic distributions and therefore may have different queuing development. One *MOVES* scenario is able to calculate the emissions from traffic in each 24 hour day and then sum up the results. For each hour, the traffic components captured in *MOVES* include the normal traffic (no lane closure), the reduced speed zone traffic (with lane closure), and the queuing zone traffic (if a queue develops). Because each lane closure scheme creates a different work zone traffic pattern, each lane closure scheme is modeled separately in *MOVES*. In addition, a *Do Nothing* scenario simulating no construction is modeled as the base case. The difference in energy consumption and GHG emission between these two scenarios is then the focus of this study.

CASE STUDIES

Case Study Description

The two asphalt and two concrete case studies presented in this study are based on those used in a previous pavement LCA study *(1)*. This study examined the life cycle energy consumption and GHG emissions under different traffic levels, construction smoothness and materials used. The results indicated that for pavement segments with high traffic volumes, the energy and GHG savings accrued during the use phase due to improved roughness can be substantially larger than the energy use and GHG emissions from material production and construction phases. The study also found for low or medium traffic volume roads, the smoothness obtained by the contractor and the material used in construction have a more substantial effect. A summary of these four case studies is provided as follows (details are in the original case studies) *(1)*.

The LCA phases considered in the modeling include material production, construction, and use. Because the routine maintenance and end-of-life (EOF) phase were assumed to be the same within each pavement type, they were omitted. However, the energy consumption and GHG emissions from the transport in the EOL phase were included.

Considering Caltrans pavement preservation treatments, the four case studies are based on the following four rural road segments (see Table 1 for details):

- An asphalt segment with a high traffic volume (KER-5),
- An asphalt segment with a low traffic volume (BUT-70),
- A concrete segment with a high traffic volume (LA-5), and
- A concrete segment with a medium traffic volume (IMP-86).

For asphalt pavement preservation, the old surface layer was milled 0.15 ft. (45 mm) and a new asphalt overlay 0.25 ft. (75 mm) was applied. The concrete pavement preservation is referred to as “Concrete Pavement Restoration B” (CPR B). In CPR B, about 3 percent of total slabs were replaced using Rapid Strength Concrete (RSC) that could be opened to traffic after 4 or 12 hours of placement, and all lanes were diamond ground after slab replacement *(10)*.

Table 1: Summary of the Four Case Studies *(1)*

Case Study	**KER-5**	**BUT-70**	**LA-5**	**IMP-86**
County	Kern	Butte	Los Angeles	Imperial
Route	I-5 Southbound	SR-70 Westbound	I-5 Southbound	SR-86 Westbound
Surface	Asphalt concrete	Asphalt concrete	Cement concrete	Cement concrete
Analysis period	5 years (starting 2012)	5 years (starting 2012)	10 years (starting 2012)	10 years (starting 2012)
Section length	10 miles (16 km)	5 miles (8 km)	10 miles (16 km)	5 miles (8 km)
Number of lanes in one direction	2	2	4	2
One-way AADT	17,000	1,600	43,000	5,600
Truck percentage	35%	15%	25%	29%
Treatment type	Mill and overlay	Mill and overlay	CPR B	CPR B

Different lane closure strategies and the resultant productivity calculated based on the Caltrans LCCA manual were used to develop the scenarios for each case study *(10)*. Table 2 shows the asphalt and concrete treatment productivity. It should be noted that the productivities in the table are under the assumption of sequential construction operations which results in a conservative estimate of the construction duration. This helps to determine the upper boundary of the impact from work zone traffic in the complete pavement life cycle.

Table 2: Preservation Treatment Productivity Table *(10)*

Final Surface Type	**Treatment Type**		**Productivity (Average lane-mile completed per closure)**				
			Daily Closure (Weekday)		**Continuous Closure**		**Weekend Closure (55-Hour)**
			5 to 7-hour closure	**8 to 12-hour closure**	**16 hour/day operation**	**24 hour/day operation**	
Asphalt	Mill and overlay		0.27	0.64	1.02	1.84	5.16
Concrete	CPR B	4-hr RSC	0.2	2.8	6.4	N/A	N/A
		12-hr RSC	N/A	N/A	1	5.8	33.2

Based on the productivity table, this study only selected the traffic closure scenarios that can represent the extreme situations to reduce modeling intensity. For asphalt case studies, three lane closure schemes were evaluated in the analysis: 5 to 7-hour closures as an example of weekday nighttime closures, 16 hours/day construction operations with 24 hour per day closures as an example of continuous closures, and a 55-hour weekend closure. The two weeknight closure types used by Caltrans (5 to 7-hour and 8 to 12-hour closures) produce similar work zone traffic patterns, but the 5 to 7-hour closure was selected to provide a more conservative estimate of construction duration. Similarly, 16 hours/day and 24 hours/day construction operations under 24 hour per day continuous closures also result in the same traffic pattern but the 16 hours/day operation has a lower productivity.

For concrete case studies, two traffic closure schemes were evaluated in the analysis: 5 to 7-hour closures using 4-hr RSC as an example of weeknight closures and 16 hours/day construction operations with continuous closures using 12-hr RSC. Other closure schemes were not selected due to similar reasons as explained in the asphalt case studies. The 55-hour Weekend closure was not selected because the work zone traffic pattern during weekend closure will be similar to the continuous closure but its productivity is more than fifteen times higher than the continuous closure (the productivity shown in the table is per closure. Therefore, because the 55-hour weekend closure includes two days, the comparison here is based on the lane-mile completed per day.). This gives the weekend closure a much shorter construction duration and a much less work zone traffic impact compared to the continuous closure. In addition, because the LA-5 case has four lanes in one direction, a 1-lane closure and a 2-lane closure schemes were also analyzed in addition to the traffic closure scheme discussed previously. Table 3 shows the final traffic closure scenarios analyzed in this study. This study used 6 hours when calculating the 5 to 7-hour closure. As explained previously, all cases were analyzed using the conservative sequential construction assumption due to the lack of productivity data in concurrent construction.

Table 3: Complete Scenarios Analyzed in this Study

Case study	Total lane-miles	Number of lanes closed	Closure type	Productivity (lane-miles per day)	Number of weekdays to complete project	Number of weekends to complete project
KER-5 (10 mile length)	20	1	5 to 7-hour weekday closure	0.27	74	0
		1	16 hour/day continuous closure	1.02	14	6
		1	55-hour weekend closure	5.16	0	8
BUT-70 (5 mile length)	10	1	5 to 7-hour weekday closure	0.27	37	0
		1	16 hour/day continuous closure	1.02	7	3
		1	55-hour weekend closure	5.16	0	4
LA-5 (10 mile length)[1]	40	1	5 to 7-hour weekday closure using 4-hr RSC	0.20	200	0
		2			200	0
		1	16 hour/day continuous closure using 12-hr RSC	1.00	28	12
		2			28	12
IMP-86 (5 mile length)	10	1	5 to 7-hour weekday closure using 4-hr RSC	0.20	50	0
		1	16 hour/day continuous closure using 12-hr RSC	1.00	7	3

Note: [1]: This study used the productivities for sequential construction in both 1-lane closure and 2-lane closure.

Results

Results of Demand vs. Capacity

Due to space limitations, the hourly demand and capacity figure under each traffic closure scenario in each case study are not shown in this paper. The results show that for the KER-5, BUT-70 and IMP-86 cases, under all closure schemes, no queue ever developed. For the LA-5 case, no queue developed under any 6-hour weeknight closure scenario (1-lane or 2-lane closure). However, under the case of 16-hour construction operations with a continuous closure, there was a small queue during the peak hour when two of the four lanes were closed, but no queue developed when only one of the lanes was closed. These results imply a very low impact from the work zone traffic in these case studies, as assumed in the original study *(1)*.

Result of Work Zone and Comparison with other Phases

Table 4 shows the energy consumption and GHG emissions due to the work zone traffic in all cases analyzed. Table 5 shows the results from all other life cycle phases extracted from the previously study for comparison *(1)*. All of the numbers shown in the tables are relative to the *Do Nothing* scenario: A positive value means a saving compared to *Do Nothing*, while a negative value indicates greater consumption or emissions than *Do Nothing*.

Table 4: Energy and GHG Saving from Work Zone Traffic Compared to *Do Nothing* all Cases

Material	Scenario		Energy saving (10^6 MJ)	GHG emission reduction (metric ton CO_2-e)
KER-5	1-lane closure	6-hour weekday daily closure	0.0587	4
		16-hour operation continuous closure	0.4300	32
		55-hour weekend closure	0.4900	36
BUT-70	1-lane closure	6-hour weekday daily closure	-0.0098	-1
		16-hour operation continuous closure	-0.0386	-3
		55-hour weekend closure	-0.0143	-1
LA-5	1-lane closure	6-hour weekday daily closure	0.1620	12
		16-hour operation continuous closure	1.4000	103
	2-lane closure	6-hour weekday daily closure	0.1620	12
		16-hour operation continuous closure	-29.900	-2,173
IMP-86	1-lane closure	6-hour weekday daily closure	-0.0735	-5
		16-hour operation continuous closure	-0.2260	-16

Comparison of the results in Tables 4 and 5 shows that in these case studies the energy consumption due to the work zone traffic is minimal compared with other phases in the pavement life cycle. In some scenarios (KER-5 and LA-5), the work zone traffic actually saves energy and reduces GHG emissions because there is no queue developing and the posted speed limit in the work zone (usually 55 mph [89 km/h] on freeways) is lower than the normal speed limit (usually 65 mph [105 km/h] on freeway),. This is because most vehicles achieve maximum fuel efficiency when travelling at steady speeds between 40 and 50 mph (64 and 80 km/h) *(11)* with decreasing fuel efficiency at speeds that are both lower and higher than this optimum range. BUT-70 and IMP-86 show additional energy consumption and GHG emissions even if there is no queue developing because these two segments are unrestricted access highways, and a different driving cycle compared with freeway was applied on these segment in *MOVES*. On unrestricted-access highways (freeways), a higher speed (the *Do Nothing* scenario) indicates less speed fluctuation and therefore lower energy consumption and GHG emissions. Nevertheless, under either scenario, the impact from work zone traffic is very small.

Table 5: Analysis Period Energy and GHG Compared to *Do Nothing* in all Cases under 0 Percent Traffic Growth except Work Zone Traffic *(1)*

Case	Construction Smoothness[1]	Feedstock Energy (106 MJ)	Material Production Energy (106 MJ)	Construction Energy (106 MJ)	Use Phase (106 MJ)	Total Energy Saving (106 MJ)	GHG Reduction (Metric Ton CO_2-e)
KER-5	*Smooth*	-33	-21.0	-7.0	100.0	74.0	5,232
	Less Smooth				72.0	44.0	3,114
BUT-70	*Smooth*	-17	-10.0	-3.5	4.7	-9.2	-721
	Less Smooth				3.6	-10.0	-798
LA-5	*Smooth*	0	-5.3	-4.4	550.0	540.0	38,507
	Less Smooth				68.0	58.0	3,751
IMP-86	*Smooth*	0	-1.3	-1.2	29.0	27.0	1,852
	Less Smooth				2.3	-0.2	-125

Note:

[1]: In the original study, *Smooth* and *Less Smooth* construction are defined as the average smoothness achieved by the contractors (represented by International Roughness Index, IRI) minus and plus two standard deviations, respectively.

When a queue develops, the energy consumption and GHG emission from work zone traffic is higher than the *Do Nothing* traffic. However, the impact under either scenario is also relatively small compared with other life cycle phases unless it happens with bad construction smoothness. This is because the GHG savings during the use phase can be substantially reduced when bad construction smoothness happens. In LA-5, during the 2-lane closure with 16-hour construction operations and a continuous closure, the additional energy consumption from the queuing traffic became significant compared with the material production and construction phases, but still smaller than the use phase effects of making the pavement smoother. However, it should be noted that this study used productivity of sequential construction in 2-lane closure, whereas in reality concurrent construction is usually used in 2-lane closure and its productivity will be higher. Therefore the actual impact will be lower than the value shown here. On a medium volume road like IMP-86, both the energy savings in the use phase due to making the pavement smoother, and the impacts from work zone traffic are lower than on the high volume roads. This is because although the energy saving in the use phase is heavily dependent on the traffic volume of the road, the work zone traffic is also heavily dependent on the traffic volume of the road. Therefore, it is safe to conclude that the impact from work zone traffic did not have an important role in the overall life cycle result for rural pavement segments as demonstrated in these case studies.

In the previous pavement LCA case studies, it was assume that all construction events happen at night so the impact from work zone traffic can be minimized. This study has shown that the nighttime closure indeed has a limited impact from work zone traffic and the previous assumption is valid.

CONCLUSIONS AND FUTURE WORK

In this study, a model was developed to characterize highway work zone traffic and assess its impact on energy consumption and GHG emissions. A demand-capacity model was used to characterize the work zone traffic, and the results from the demand-capacity model were used as the inputs to the *MOVES* model to calculate the energy consumption and GHG emissions. The cases from a previous pavement LCA study were used to evaluate the impacts from the rural highway work zone traffic for typical highway maintenance treatments intended to make the pavement smoother and its significance, compared with the results from the other life cycle phases; feedstock, material production, and use (change of smoothness) phases.

The case studies have led to following conclusions:

- For rural areas, the energy consumption and GHG emissions affected by the work zone traffic were insignificant compared to those affected by the other life cycle phases. Therefore, the assumption made in the previous study, that the impact of work zone traffic during nighttime construction is negligible, is valid. However, case studies that represent urban areas where traffic volume is close to highway capacity should be performed in the future to examine the impacts from work zone traffic under these situations.
- If no queue develops, there can be energy savings and GHG emissions reduction due to the lower traffic speeds in the work zone. However, the energy and GHG saving from the reduced speed is very small.
- The only extreme situation, where the traffic delay effect can account for up to 50 percent of the life cycle result, was the continuous construction event with half of the lanes closure on a high traffic volume segment with very low quality smoothness. However, such scenario is less likely to happen in reality because the actual productivity using concurrent construction is higher than the value used in this study, which reduces the construction duration and the impacts from work zone traffic.

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