

Article

An Application of Discrete-Event Simulation in Estimating Emissions from Equipment Operations in Flexible Pavement Construction Projects

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Abstract. This paper presents a comprehensive model with an application of discrete-event simulation (DES) that facilitates an estimation of CO₂ emissions resulting from equipment operation in flexible pavement construction. While there are a number of past studies applying a DES technique to the construction process, they mostly concentrate on a single process rather than an entire project. The constructed model aims to improve the current body of knowledge in two aspects: (1) the development of a comprehensive construction operation diagram representing flexible pavement construction and (2) the application of DES that contributes to a more reliable result of the environmental impact. An application example of the real expressway project in Thailand was analyzed to demonstrate the use and capabilities of the developed model in evaluating the environmental impact in terms of CO₂ emissions. The findings will provide a holistic environmental perspective to transportation planners and help them in analyzing their resource allocation in order to make the projects more eco-friendly.

Keywords: Discrete-event simulation, carbon dioxide emissions, flexible pavement, construction operations, construction equipment.

ENGINEERING JOURNAL Volume 21 Issue 7

Received 7 April 2017

Accepted 30 May 2017

Published 29 December 2017

Online at <http://www.engj.org/>

DOI:10.4186/ej.2017.21.7.197

1. Introduction

The issues of climate change and global warming potential have driven serious discussions among industrial entities. Several regulations and agreements have been released to stimulate significant efforts toward environmental impact mitigation. For instance, the Kyoto Protocol Treaty was launched in 1998 as a binding agreement between nations with GHG emission reduction targets in order to mandate their sustainability performance [1]. The Fixing American's Surface Transportation Act (FAST Act) [2] and the Moving Ahead for Progress in the 21st Century Act (MAP-21) [3] are two more examples of federal regulations that were initiated by the US government in order to improve the national transportation performance in several aspects, including sustainability.

Among industrial sectors, transportation is the second highest GHG contributor, ranking just behind the electricity sector, with more than 1.7 trillion tons of CO₂ equivalent in 2014 [4]. Considering construction equipment, the amount of CO₂ emission has increased over the past decades and accounts for 40% of total CO₂ emissions from non-road vehicles [5, 6]. However, the past literature on environmental impact reduction in highway projects has focused merely on material selection [7-10] during the design phase, mitigation action in the operation phase [11-13], and reclamation of wasted materials after demolition [14-15]. This attention prevents a holistic view of project planners on construction sustainability with lack of direct perception on the impacts from construction processes. Therefore, a novel approach in estimating CO₂ emissions from construction operation activities is pressingly needed in order to enhance sustainable construction in highway transportation projects.

To this end, a simple-yet-systematic methodology is necessitated to construct a reliable and accurate measurement of onsite CO₂ emissions from construction equipment. Since Discrete-event simulation (DES) has been renowned as a powerful technique in analyzing complex construction processes [16-17], there is significant evidence of implementing the DES method in many past studies (see [18-23]). As a result, several DES tools have been developed to facilitate system modeling, such as CYCLONE [24] and STROBOSCOPE [25]. Among those simulation tools, EZStrobe has been widely recognized with its capability, which is easy to learn and has little effort required for analysis [18]. With the capabilities of DES, more reliable results can be expected in estimating equipment emissions when compared to a traditional approach. The DES can closely imitate the reality of construction projects. For example, CO₂ emissions from the idle time of operating machines can be known from the number of resources waiting in queues.

As mentioned before, the literature has revealed an application of DES in analyzing construction processes. Nevertheless, past studies mostly considered a single construction operation, such as the earth-moving, cement-loading, and precast slab installation operation (see [16], [18], [20], [22]). Although there have been some attempts in constructing a systematic model for construction processes in highway projects [16, 21], no research purposes a comprehensive paradigm that presents a high-detailed levels of resources, activities, and links sufficient for quantifying CO₂ emissions along entire processes in a highway pavement construction project.

To address the research gaps, this study presents a comprehensive model that adopts a DES technique to facilitate an estimation of CO₂ emissions resulting from the fuel consumption of construction equipment operations. The flexible pavement construction project is emphasized in this paper due to a large number of these pavement structures in Thailand. The model is developed by considering construction processes over all structural layers with capabilities in: (1) applying the DES in modeling complex highway construction processes; and (2) quantifying the amount of CO₂ generated during the construction process due to the equipment combustion process. The details and descriptions of the developed model are given in the following sections.

2. DES Modeling for Equipment Operations

This section introduces the concept of applying the DES technique in order to analyze equipment operations over entire processes of flexible pavement construction. The rest of this section presents the basic background on DES, and model development with the systematic schemes in the form of an Activity Cycle Diagram (ACD), as follows.

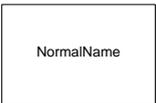
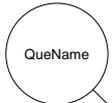
2.1. Background

DES is a modeling technique that has been widely used to analyze complex, interactive and dynamic construction operations in construction projects over the past decades [16]. According to [17], DES has been acknowledged as a powerful simulation technique that is capable of analyzing processes or operations of construction projects with a representation of a real operational system [26]. Based on the literature, several studies have applied DES in the research area of construction engineering and management. For example, [27-29] used DES in evaluating the environmental impacts due to construction. Another example is an application of DES in construction planning as a result of heavy equipment usage, such as in [30-31].

In fact, several construction-oriented languages have been designed for analyzing simulation systems, such as CYCLONE [24] and STROBOSCOPE [25], for different purposes and different levels of analyses. However, this study adopted EZStrobe, as it is simple and easy to use [18], with the development of the Microsoft Visio interface for model formation. The simulation modeling starts with the development of ACD that graphically presents the systematic network with basic modeling elements representing activities, resources, and their interactions. The following paragraph provides a brief description of modeling instructions, rules, and basic elements of EZStrobe. However, their inclusive instructions can be found in [18] and [32].

EZtrobe is a simple and easy-to-learn simulation tool that employs the Microsoft Visual graphical interface for constructing ACD that represents activities, resources, and links of a real system. All components in ACD will be represented by one of the following basic elements: Combi, Normal, Queue, Fork, or Link that have a different shape. The explanation and restriction of each element are introduced, as shown in Table 1.

Table 1. Basic elements in EZStrobe.

Basic Element	Description	Restriction
	A Combi represents a constrained activity. Its start will be triggered by the availability of required resources.	A Combi can only follow Queues, but be placed before any other node except a Combi.
	A Normal represents an unconstrained activity. It will start depending on the completion of preceding activities.	A Normal can follow any node other than a Queue, and be placed before any node except a Combi.
	A Queue represents idle resources that are stored for use in a succeeding Combi.	A Queue can follow any other node other than a Queue and precede only a Combi.
	A Fork represents a probabilistic routing element that triggers a branch selection to the succeeding element.	A Fork typically follows a Combi or Normal but can also follow another Fork.
	A Link represents a connectivity between different activities and queues. There are three types of Links with different functionality: Draw Link, Release Link, and Branch Link.	

2.2. Model Development

In this paper, the model starts from constructing the ACDs that are able to illustrate an inclusive picture of construction processes and resources used in constructing structural layers for highway pavement projects. The system diagrams were first constructed based on literature works on highway flexible pavement construction (e.g. [18], [21], [29], [33-35]). Their completeness and reliability were verified by the interview of the project engineer, who has worked in a transportation agency and has experienced highway construction projects for 5-10 years.

The constructed ACDs were afterwards implemented on the case study of the real expressway project in Thailand. However, this paper employed the project data only from the part of road pavement construction, as the entire construction project covers other facilities, such as the toll plaza, toll surveillance building, weight station, and toll collection and the traffic control system that are beyond the scope of this paper. The case study covers a road pavement constructed on the ground, which is an extension part linking the city road to the expressway. Please also note that a length of 1 kilometer, as a representative distance, was expanded from the original scope of road pavement construction in order to realistically and explicitly demonstrate the environmental impact of typical highway construction per one unit length. The following sections demonstrate the developed ACDs of the case study with detailed descriptions for flexible pavement structural layers, starting from the subgrade, subbase, base, and then the surface layer, respectively. It is also worth noting that input parameters stated in the ACDs are typically assigned based on the actual data in the construction site. For instance, a number written in a QUEUE represents an available resource or an amount of work to be completed. A type of duration distribution along with relevant parameters mentioned in a NORMAL or COMBI represents a duration to complete such construction activity. However, in this paper, the authors adopted the activity duration and distribution from the case studies in the past literature (i.e. [18], [21], and [29]). In fact, this adoption has an insignificant impact on the result and does not distort the result's interpretation, as the input parameters typically vary based on specific characteristics of a construction project.

2.2.1. Subgrade layer

The first part of the model is the construction of the subgrade layer by improving the mechanical properties of in-place soil or fill materials to support pavement structures. Starting with the site preparation, all utilities necessary for construction should be prepared and planned. The construction site should be cleared and ready for construction. All excessive substances, such as vegetation, stumps, and unsuitable soil, have to be removed. Next, a grader or trimmer will be operated for better grade control and tolerance.

A suitable type of roller and compactor are then applied to increase the strength and improve the soil properties. The compaction is always necessary in order to ensure an achievement of the desired strength and properties. Figure 1 demonstrates the conceptual model representing the processes and resources for the subgrade layer construction.

The typical construction method for the subgrade layer construction mainly proceeds on grading and compacting works, as shown in Fig. 1. Here, the simulation model was simplified to include the operations of graders and compactors with an assumption that the clearing and grubbing processes have been previously completed. The process is designed to start with graders in the "Grader" QUEUE to shape the construction area, and then follows with pneumatic rollers in the "PR" QUEUE to ensure the load-bearing capacity. Two main construction processes were included in Fig. 1 with the following details.

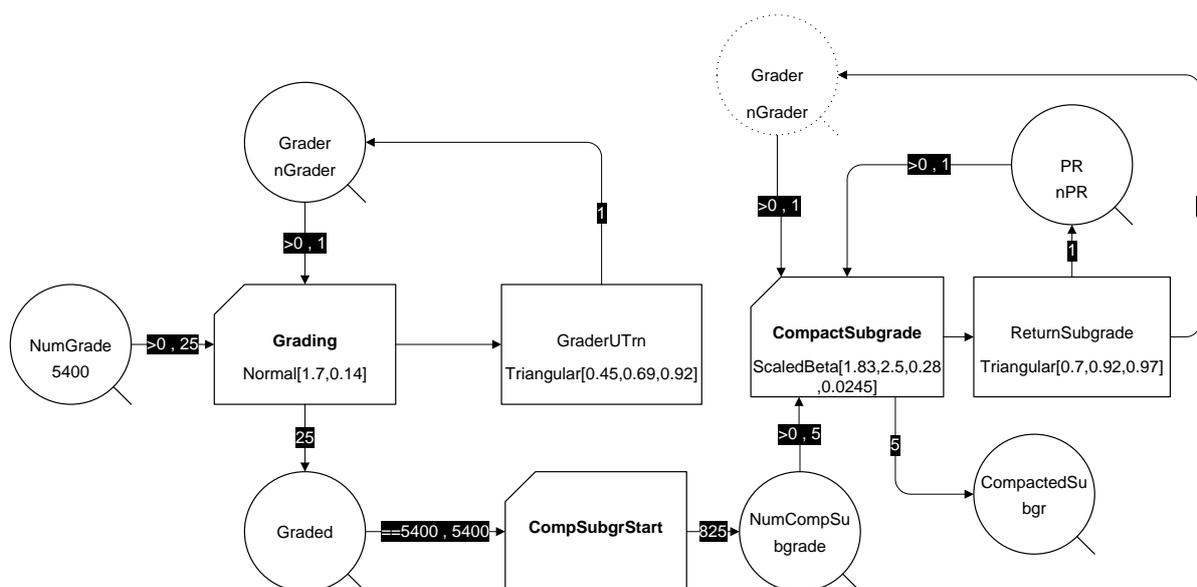


Fig. 1. EZStrobe ACD: grading and compacting for the subgrade layer.

Cycle 1 This cycle represents the operation of a grader in removing the unsuitable subgrade and smoothing the surface. The total area that requires grading will be defined in the “NumGrade” QUEUE. For each cycle, a grader will grade and then return to start a new round after completion, according to the “Grading” COMBI and “GraderUTrn” NORMAL, respectively. The total number of graded areas will be added into the “Graded” QUEUE, which represents the area that graders have completely graded.

Cycle 2 This cycle is for the compacting work that will start upon the completion of the previous cycle at the “ComSubgrStart” COMBI. The graders and pneumatic rollers will consecutively work to proceed compacting in the “CompactSubgrade” COMBI and “ReturnSubgrade” NORMAL on the number of jobs that require compacting in the “NumCompSubgrade” QUEUE.

2.2.2. Subbase and base layer

With the similarity of construction processes, the second part introduces the schematic diagrams that can be applied for both subbase and base layer construction. This part is separated into three consecutive components: material delivery, material stabilizing, and compacting work, as shown in Figs. 2 to 4.

The first component mainly focuses on material transportation with the utilization of two types of equipment, which are excavator and dump truck. As such, Fig. 2 includes two cycles of activity, with one for an excavator’s operation and another for a dump truck’s. The equipment are assumed to carry a certain amount of material in the “SBMat” QUEUE, with a number of excavators in the “Excavator” QUEUE at the borrow pit. The excavator cycle consists of four activities, starting from “Excavate,” “SwingWithMat,” “Loading,” and “Swing Empty.” The “Loading” COMBI links the excavator and the dump truck cycles, as it represents when the material is loaded into a truck. The excavator cycle will be repetitive until the load in a dump truck (see the “SBinTruck” QUEUE) reaches a certain amount that is sufficient for hauling (see the “ReadyToGo” COMBI). The total number of excavator swings will be controlled by the “NumOfSwing” QUEUE. The loading activity requires a dump truck to maneuver and wait for the full load at the “Maneuver” COMBI under the limitation of loading space identified in the “LoadingSp” QUEUE.

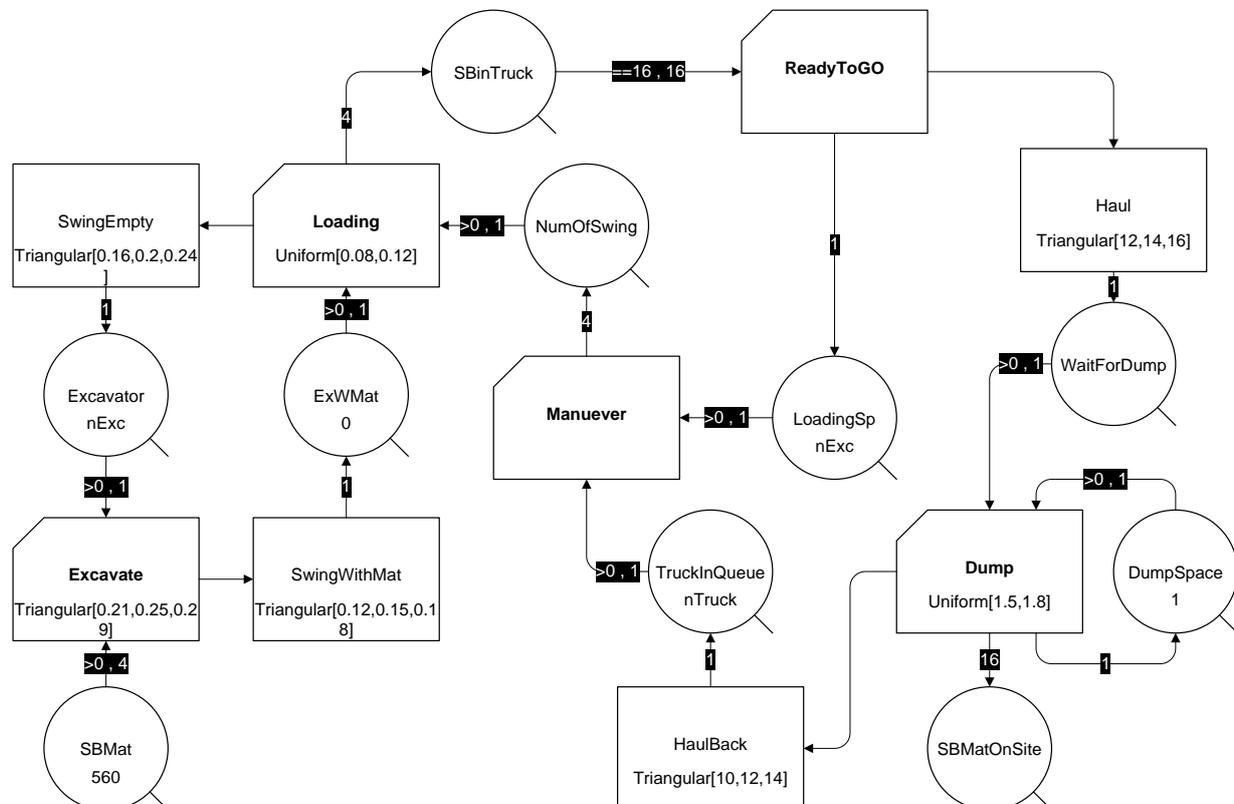


Fig. 2. EZStrobe ACD: material delivery for the subbase or base layer.

water in the “GoToRefill” and “RefillWater” NORMAL, respectively. Figure 3 adopts FORK as an element in initiating the process of water refill. The operation will consider the what-if condition written on the link by counting the number of current elements in the “RdWater” QUEUE. That means that when it reaches a predetermined number, the truck will proceed to refill the tank. A constraint is presumably added in Fig. 3 by allowing one truck working at a time. This forces the filled truck to wait for an available space at the “WTruck” QUEUE. In this study, the modeler has created the “TicketToSpray” QUEUE as an imaginary element representing the available space for the next water-spraying truck.

The third component considers the compacting work, as shown in Fig. 4. Three types of construction equipment are listed in the operation—grader, pneumatic roller, and tandem vibratory roller. All equipment will work together in sequence to improve strength and properties of the filled material. The construction process consists of three main activity cycles, as follows.

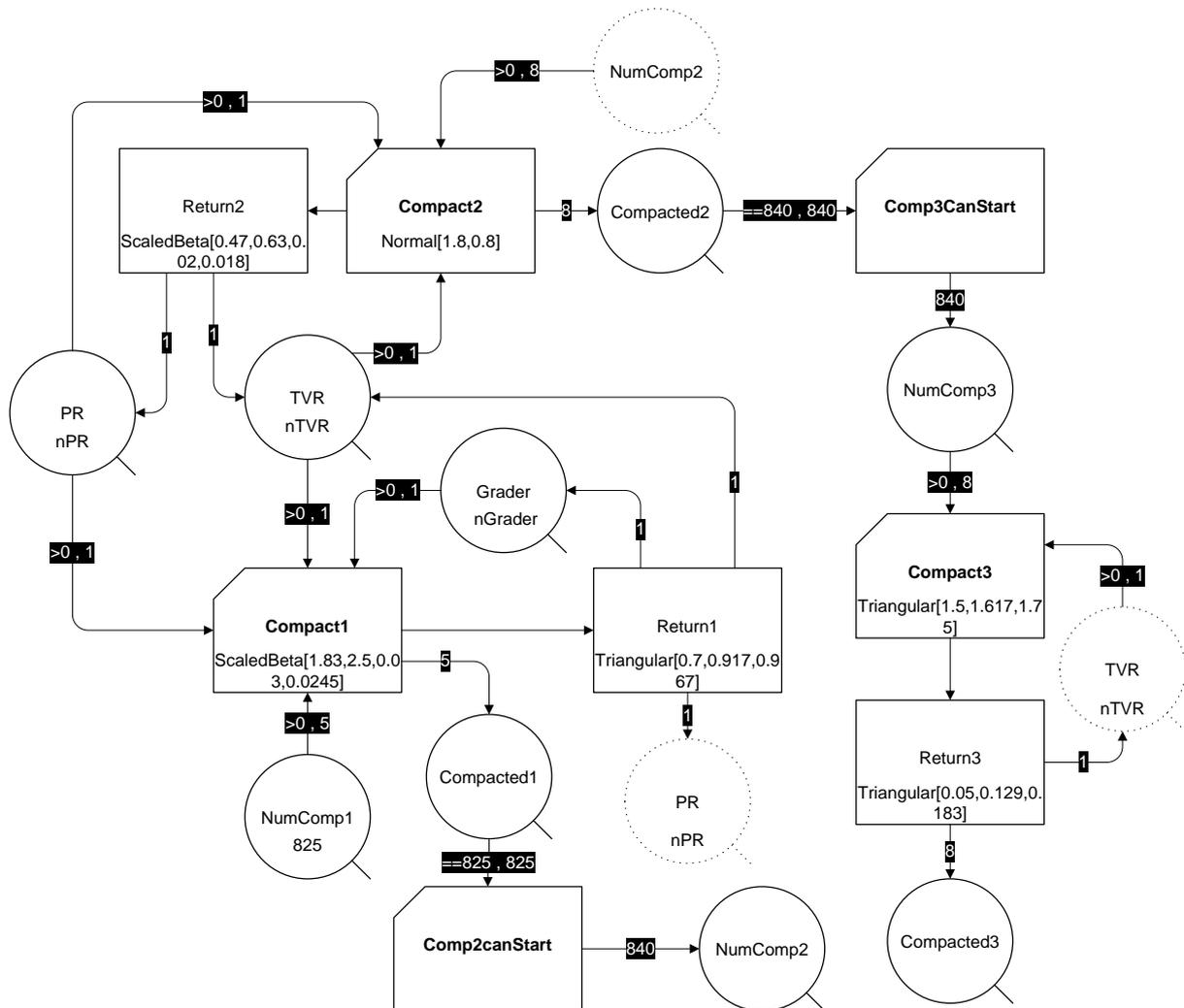


Fig. 4. EZStrobe ACD: compacting for the subbase or base layer.

Cycle 1 In the first cycle, a grader (in the “Grader” QUEUE), pneumatic roller (in the “PR” QUEUE), and tandem vibratory roller (in the “TVR” QUEUE) will work in sequence. The total number of materials need for the 1st cycle’s operation is identified in the “NumComp1” QUEUE. A grader will first start grading to shape the stabilized material and prepare for the compacting work. A pneumatic roller and tandem vibratory roller, respectively, will then work right away after the grader. The operation will work at the “Compact1” COMBI and reverse for a new round at the “Return1” NORMAL. This process will be repetitive until the structural layer is well formed. The quantity of compacted material will be counted in the “Compacted1” QUEUE.

Cycle 2 This cycle is operated by a pneumatic roller and tandem vibratory roller. After the previous cycle is completed, the grader has stopped and only rollers will continue on the preliminary compacting task. In the diagram, the cycle is initiated after a certain amount of material was completed from the 1st cycle. The 2nd cycle will be exercised to start from the “Comp2canStart” COMBI by assigning material to the “NumComp2” QUEUE. The equipment will operate to compact the assigned resources repetitively through the “Compact2” COMBI and “Return2” NORMAL. Similarly, the compacted material will transfer to the “Compacted2” QUEUE in order to launch the next cycle.

Cycle 3 The last cycle commences after the predefined material was drawn into the “NumComp3” QUEUE. The tandem vibratory roller will repeatedly compact until the desired density of material is met (see the “Compact3” COMBI and “Return3” NORMAL).

2.2.3. Surface layer

The last component emphasizes the construction of the pavement surface layer with an application of hot-mixed asphalt (HMA) topped on the base layer. First, the base surface should be clean and well-prepared for prime coat spraying and then HMA paving. The truck is employed in the construction to transport HMA from the production plant to the site location. The transported HMA can be directly dumped into the paver or placed on the being-paved surface. Sometimes, a transfer vehicle or pick-up machine will be used to feed HMA into the paver, depending on working conditions. The HMA mixture will then be laid down and compacted by rollers and compactors with an appropriate procedure to ensure adequate compaction.

Figure 5 demonstrates the asphalt material transportation and paving tasks for surface layer construction. It is composed of four main activity cycles. The first cycle starts when the asphalt material is loaded into the hauling truck (at the “LoadPavMat” COMBI) and delivered from the production plant to the construction site (see the “TrkToSite” NORMAL). The material is then dumped into a paver at the “Dump” COMBI, which is also the link point to the 2nd cycle. The paver will lay the asphalt material down on the surface at the “Paving” NORMAL by using a number of pavers available in the “Paver” QUEUE. Concurrently, the empty truck in the 1st cycle is hauling back to get a new load of material at the plant (see the “BackToPlant” NORMAL). Please note that the limitation of load space at the production plant can be identified, as shown in Fig. 5, with the use of the “HopperSpace” QUEUE in order to limit the number of being-loaded trucks at a time.

The 3rd and 4th cycles concentrate on the compacting activities by the employing pneumatic roller and tandem vibratory roller. Their explanations will be omitted here, as the model mechanisms are similar to the one mentioned in the previous section.

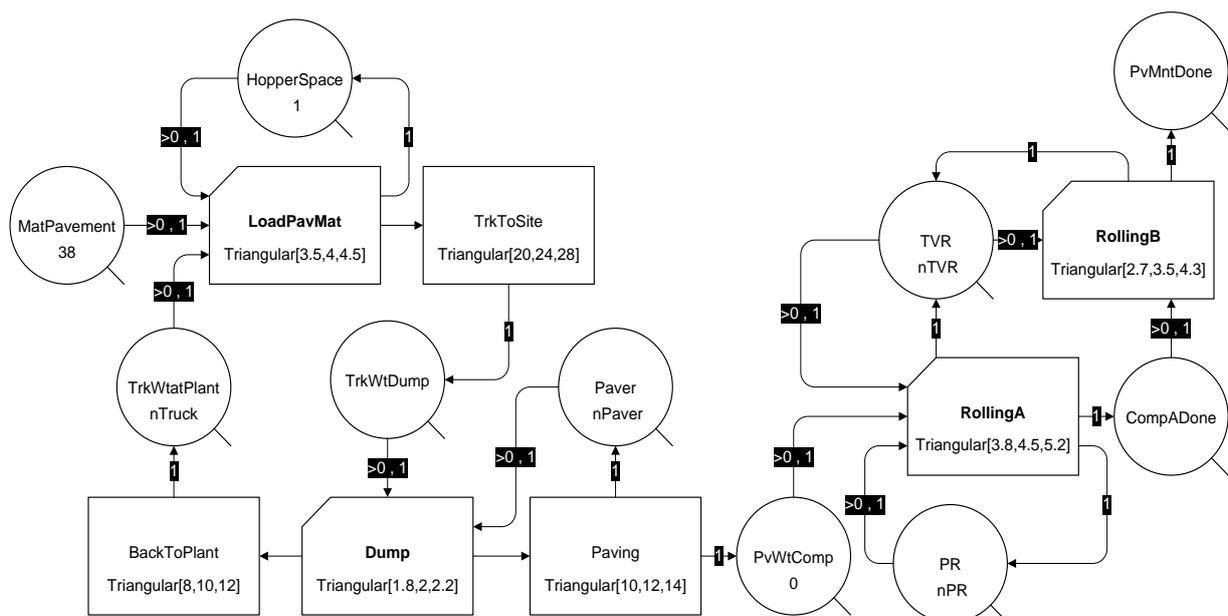


Fig. 5. EZStrobe ACD: asphalt material delivery and laying for the surface layer.

Considering Figs. 1-5, it is noteworthy that a hauling distance between a construction site and stockpiles, an asphalt production plant or even a water-refilling area can affect the equipment's working duration. A long distance will directly lead to a higher working time and therefore an environmental impact. On the other hand, an idle time is mainly subject to the equipment configuration identified in any construction process. This means an optimum equipment combination can effectively decrease the equipment's idle time through the construction process. In this paper, the hauling distance was not numerically defined, as its impact on the working and idle time was included in an activity duration, which is represented in the form of an activity duration distribution written in an ACD.

3. An Estimation of CO₂ Emissions

This section proposes the calculation method that can be used for evaluating the impact of heavy equipment operations on the environment during project construction. From the literature review, the existing practices in estimating construction emissions mainly depend on the NONROAD model, developed by the United States Environmental Protection Agency, with the following equation [6, 36, 37].

$$E = EP \times OT \times EF \times LF \quad (1)$$

where E = emissions; EP = engine power (hp); OT = operating time (hr); EF = emission factor (g/hp-hr); and LF = load factor. Engine power and emission factor are directly related to equipment properties and characteristics, such as type and engine specification. On the other hand, operating time and load factor are associated with both the equipment properties and their operational pattern. Operating time can be purely determined from the actual time of equipment working on the field, while load factor is identified as the ratio of the maximum utilizing power of the equipment engine when being operated, which includes the effects from idling, partial load, and transient operation [36, 38]. Nevertheless, the existing model proposes the engine load factor as an average value from an empirical test in a laboratory that is highly correlated to specific equipment, construction activity, and site conditions [39]. As a result, using the average load factor may prevent transportation planners from having a realistic view about the emissions in a construction project.

In order to address this burdensome issue, this paper introduces a novel framework for an estimation of CO₂ emissions caused by the equipment operations. The equipment operating and the waiting time from the DES analysis will be used as a number of working hours and idle time of equipment, and then will be integrated with the proposed framework to support an estimation. To this end, the framework is newly developed with the following equation.

$$E = (WT \times FCW \times EF) + (IT \times FCI \times EF) \quad (2)$$

where E = emissions; WT = working hour (hr); IT = idle time (s); FCW = fuel consumption rate at working conditions (L/hr); FCI = fuel consumption at idling (mL/s); and EF = emission factor (kg of CO₂/ liter). The working and idle time will be examined based on the simulation run. The rate of fuel consumption can be retrieved from the literature review. For example, [40] mentioned the consumption rate of equipment used in the highway construction project, while the fuel consumption at idling can be presumably referred to from [41]. In addition, the CO₂ emission factor, which depends on the fuel type, can be applied from [42].

For a project's construction, the environmental impacts calculated from Eq. (1) and (2) may be difficult to numerically compare because of their different levels of analyses and assumptions. As briefly mentioned earlier, NONROAD is one of the well-known models developed by the US government agency for estimating the pollutants by considering engine horse power, operating duration, emission rate, and equipment load factor. According to the literature [6, 38], the load factor is problematic that primarily prevents a realistic emission quantification. The model usually uses an average values according to a broad equipment categorization in a predetermined regional area. Otherwise, very intensive field data, such as fuel specifications and ambient temperature, are recommended for estimating load factor. However, in fact, construction projects inherently involve uncertainty and a stochastic nature that is uniquely varied. This requires significant efforts and intensive costs for data collection. The proposed model is therefore constructed with respect to an integration of the DES technique and Eq. (2) in estimating CO₂ emissions. It aims to apply DES in order to simulate the realistic characteristics and attributes of a real construction system, which is complicated and somehow impossible to directly measure on site.

The following example demonstrates the detailed calculation of how to find the working hour, idle time and amount of CO₂ emissions for surface layer construction. First of all, it is necessary to briefly mention that EZStrobe is capable of parameterizing input data and customizing analysis output. Table 2 provides all input parameters defined for surface layer construction in Fig. 5. Please note that the number of graders, trucks, pneumatic rollers, and tandem vibratory rollers in this example were equally assumed to be one.

Table 2. Input parameters for surface layer construction analysis.

Parameter	Description	Value	Reference
nPaver	Number of pavers	1	N/A
nPR	Number of pneumatic rollers (PR)	1	N/A
nTVR	Number of tandem vibratory rollers (TVR)	1	N/A
nTruck	Number of trucks	1	N/A
FCWpaver	Fuel consumption rate of paver at working condition (liter/hour)	13	[40]
FCIpaver	Fuel consumption rate of paver at idling (milliliter/second)	0.9	[41]
FCWpr	Fuel consumption rate of PR at working condition (liter/hour)	8.4	[40]
FCIpr	Fuel consumption rate of PR at idling (milliliter/second)	0.9	[41]
FCWtvr	Fuel consumption rate of TVR at working condition (liter/hour)	14.4	[40]
FCItvr	Fuel consumption rate of TVR at idling (milliliter/second)	0.9	[41]
FCWtruck	Fuel consumption rate of TVR at working condition (liter/hour)	15.9	[40]
FCItruck	Fuel consumption rate of TVR at idling (milliliter/second)	0.9	[41]
EFdiesel	Emission factor of diesel (kg of CO ₂ /liter)	2.668	[42]
EFgasoline	Emission factor of gasoline (kg of CO ₂ /liter)	2.325	[42]

Generally, EZStrobe allows the modeler to customize an analysis output by constructing formulae that are associated to input parameters and statistical results from model execution. As a result, this example adopted the statistics of total number and average duration of associated instances in order to find the working time. Similarly, the idle time can be determined from the average content of the associated queue and total simulation time. The working and idle time will be evaluated as the total duration to complete an identified process. Given that the total working and idle time of the paver from the simulation are 537.2 and 1,006.3 mins, the amount of CO₂ emissions from the paver operation can be calculated from Eq. (2), as follows:

$$\begin{aligned} \text{CO}_2 \text{ emissions from paver operation} &= (537.2 \text{ min}) \times (13 \text{ liter/hour}) \times (2.668 \text{ kg of CO}_2/\text{liter}) \times (1/60) \\ &= 310.5 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{CO}_2 \text{ emissions from paver idling} &= (1,006.3 \text{ min}) \times (0.9 \text{ mL/sec}) \times (2.668 \text{ kg of CO}_2/\text{liter}) \times (3.6) \times (1/60) \\ &= 144.9 \text{ kg} \end{aligned}$$

4. Analysis Results

The objective of this section is to demonstrate the performance and capabilities of the developed model in analyzing the impact of construction equipment operations on the environment in terms of CO₂ emissions as a result of equipment engine combustion. The model proficiently presents its capability in estimating the amount of CO₂ emitted during pavement construction, and can be useful for transportation practitioners in expanding the current planning paradigm with a sustainable perspective.

Further analysis was performed and investigated to show how much the equipment usage pattern affects the environment and the recommendations of how to reduce emissions from the construction equipment usage. First, Table 3 shows the total amount of CO₂ emissions due to equipment operations for all structural layers. The results were estimated by adopting the aforementioned ACDs and Eq. (2) in order to determine working duration, idle time, and therefore emissions. The finding presents the highest impact from the base layer construction resulting from the usage of the excavator, truck, motor grader, water truck, pneumatic roller, and tandem vibratory roller. Moreover, the analysis demonstrates the significant impact of equipment idling, which accounts for more than 10% of total CO₂ generated throughout pavement construction. This

number highlights the importance of proper resource allocation that contributes to a reduction in equipment idling and therefore environmental impact.

Table 3. CO₂ emissions during the construction process in each pavement structural layer.

Structural Layer	CO ₂ Emissions (kg of CO ₂ equivalent)	
	Equipment Operation	Equipment Idling
Subgrade	574.2	74.3
Subbase	2,529.7	221.8
Base	9,528.5	823.9
Surface	1,653.2	522.8
Total Emissions	14,285.6	1,642.7

Next, more details of equipment usage in constructing each structural layer were analyzed and given in Table 4. The data depicts the working time, idle time, and percent utilization of all equipment used during the construction. The percentage of equipment utilization represents an equipment effectiveness that is a measure of actual work earned against the expected amount of work that could be received under a certain period of time. A construction process that needs a new equipment configuration can be specified based on a low utilization of some equipment in a construction activity. In this paper, the result shows that an equipment configuration should be reconsidered in every process, except the material stabilizing that shows the percentage of equipment utilization close to one. The transportation planner may increase a similar number of motor graders and water trucks if a reduction in total duration is preferred. However, increasing equipment will definitely affect total project cost, either from renting or purchasing more equipment.

Table 4. Working time, idle time and percent utilization of each type of equipment.

Structural Layer	Equipment	Working Time (min)	Idle Time (min)	Equipment Utilization (%)
Subgrade	Grader	515.9	0.0	100.0%
	PR	542.3	515.9	51.2%
Subbase - material delivery	Excavator	98.0	937.5	9.5%
	Truck	971.7	0.0	100.0%
Subbase - material stabilizing	Grader	520.1	1.9	99.6%
	Water Truck	466.1	0.0	100.0%
Subbase - compacting	Grader	501.2	417.8	54.5%
	PR	736.9	182.2	80.2%
	TVR	919.1	0.0	100.0%
Base - material delivery	Excavator	349.6	3,381.6	9.4%
	Truck	3,506.6	0.0	100.0%
Base - material stabilizing	Grader	1,956.1	1.9	99.9%
	Water Truck	1,749.0	0.0	100.0%
Base - compacting	Grader	1,915.4	1,648.5	53.7%
	PR	2,877.3	686.6	80.7%
	TVR	3,563.9	0.0	100.0%
Surface	Paver	537.2	1,006.3	34.8%
	PR	170.6	1,372.8	11.1%
	TVR	305.6	1,237.9	19.8%
	Truck	1,532.1	11.4	99.3%

From the analysis, it also reveals the correlation between equipment utilization and idle time. The equipment with a low percentage of utilization will show a high idle time. Given that the equipment working time is constant in any construction process, the idle time plays a very important role in generating CO₂

emissions during the construction phase. Therefore, reducing the idle time with effective equipment allocation can significantly contribute to a decrease of CO₂ emissions during pavement construction. An effective allocation strategy can be established by determining a proportion between each type of equipment needed in a construction process. The apportionment of equipment must be done in order to reduce the idle time and increase the overall utilization of every type of equipment used in the process as much as possible.

In addition, the analysis was performed to illustrate the relationship between total duration and CO₂ emissions, as shown in Fig. 6. All figures shows a similar correlation between total duration and CO₂ emissions, with an optimum or near-optimum point that can lead to the lowest CO₂ emissions at a certain point of total duration. Considering the left part of the lowest point in the curves, it supports the impact of the equipment allocation strategy on CO₂ emissions. The equipment in an activity cycle should be assigned to work with a high utilization. It clearly presents that putting more resources in any construction process usually reduces total duration but sometimes results in a higher idle time and CO₂ emissions, especially when the resource is not properly allocated.

After an optimum point, an insignificant relationship is shown between total duration and CO₂ emissions in many construction processes (see Fig. 6.), as the graph tends to be a straight vertical line. This means CO₂ emission is not directly correlated to total duration after a certain point (the lowest point on the graph). Theoretically, this point represents an optimum or near-optimum situation in which all equipment is effectively allocated to perform a construction process, or some types of equipment are already employed with a very high percent of utilization.

The analysis results give a general idea of how significant the amount of CO₂ emissions from the equipment operations per 1 unit length of road is. This finding can be applied to other similar highway projects in order to approximate total CO₂ emissions due to construction equipment operations. Some input parameters may need to be reconsidered, such as an activity sequence, equipment availability, and activity duration, in order to meet the specific project characteristics. However, the developed ACDs is limited for an implementation only on the flexible pavement. Some adjustments may be needed for the rigid pavement construction project.

It is noteworthy that the analysis was performed on a 1-kilometer road pavement. The impact of CO₂ emissions due to the different equipment allocation can be significantly larger when being applied to a real construction project that covers a long distance. The dimension of construction cost was also negligible from this paper. However, transportation planners and decision makers should take the construction cost into consideration when adopting the developed model. It has been acknowledged that the project cost has an inverse relationship to the project duration due to an increase in resources. The relationship between cost and environmental impact, as well as cost, time and environmental impact, are, however, still under investigation, especially in pavement construction. Therefore, further work is recommended to examine the relationships between these three dimensions to facilitate the decision making of transportation agencies before initiating project construction.

5. Conclusions

This paper enhances the current body of knowledge in estimating CO₂ emission resulting from equipment usage during construction in flexible pavement projects. A novel model aims to improve existing studies in two aspects: (1) the development of a comprehensive construction operation module and (2) the introduction of the novel CO₂ emission estimating framework and DES application to establish more reliable results. The case study of the real expressway project in Thailand was implemented in this study in order to present performance and capabilities of the developed model. The analysis result highlights the significance of effective resource allocation on the increase of equipment utilization, as well as a reduction in equipment idle time and, therefore, environmental impact. The developed model enables transportation agencies to thoroughly evaluate the impacts of pavement construction projects on the environment and promote a sustainable consciousness in the construction industry. The result can be integrated with the other stages throughout the project's life cycle in order to holistically illustrate the entire impact.

The methodology presented in this study can be extended to other types of projects, especially the ones that require a large fleet of heavy equipment, such as rigid pavement, bridges, and dam construction. Moreover, further development will be performed to examine the trade-off relationship between three significant components—cost, time, and environmental impact—in order to simultaneously utilize construction resources and foster sustainability.

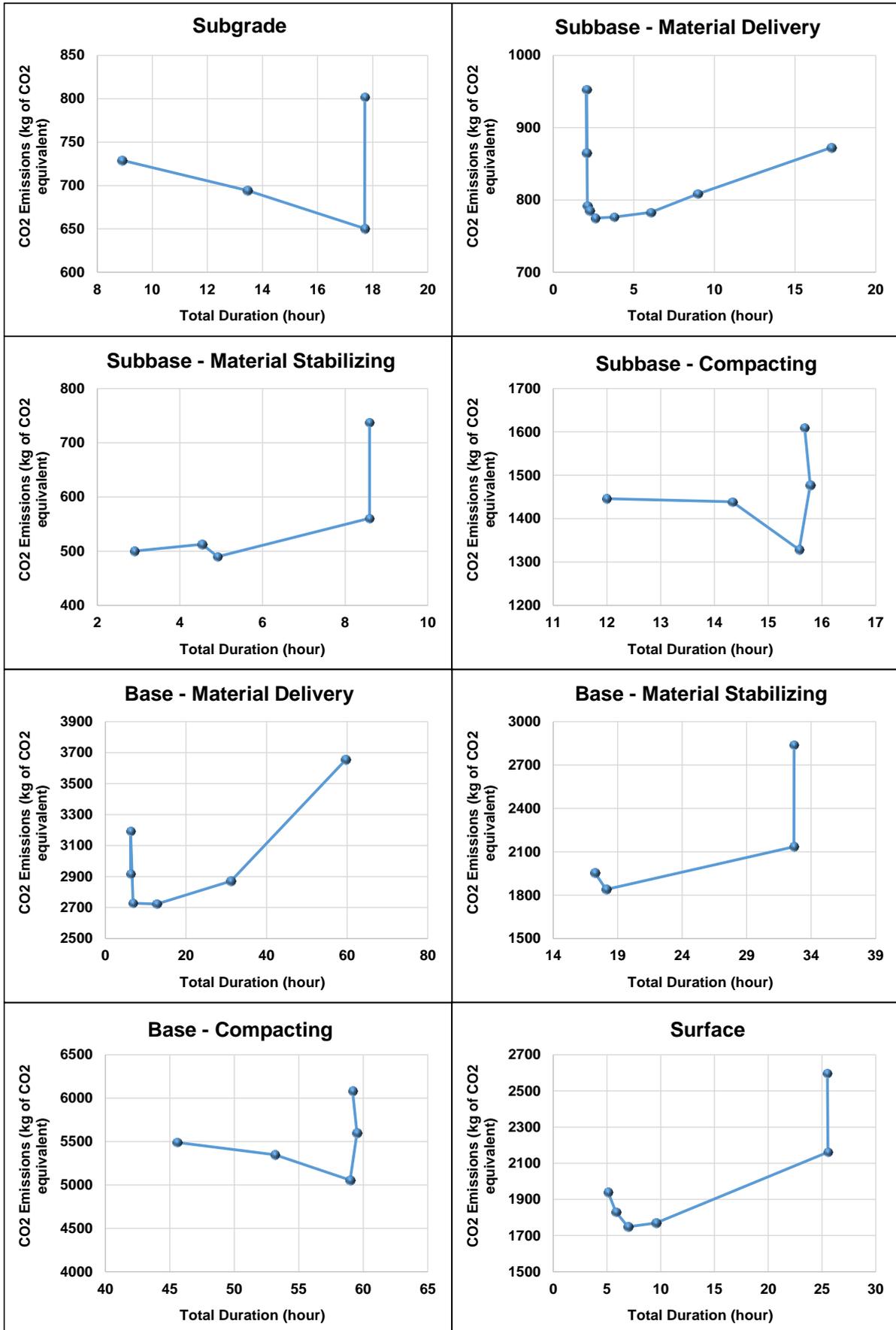


Fig. 6. Relationships between total duration and CO₂ emissions in pavement structural layers.

Acknowledgement

The data in this paper is part of expressway project construction. The authors would like to greatly thank the Expressway Authority of Thailand for providing the informative data used in the application example to facilitate the demonstration of the model's performance and capabilities. However, any opinions, findings, and recommendations written in this paper are those of the authors and do not necessarily reflect any opinions of the Expressway Authority of Thailand.

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