

SUSTAINABILITY TOOLKIT FOR SIMULATION-BASED LOGISTICS DECISIONS

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ABSTRACT

As sustainability related issues, such as energy consumption and environmental impact issues are becoming a more integrated part of operational and long-term planning decisions, simulation modeling and analysis tools are needed to aid in the decision-making process. In this paper we introduce the concept of a simulation-based sustainability toolkit and present a prototype of one portion of the toolkit that is being developed for modeling and simulating sustainability aspects of logistics and transportation systems. The sustainability simulation toolkit contains a flexible framework to enable the simulation modeling and analysis of sustainability-related factors and performance measures. This toolkit is designed for ease of implementation, so decision-makers can have sustainability measures as readily available as traditional performance measures when making logistics and transportation decisions.

1 INTRODUCTION

Sustainability related issues, such as energy consumption, emissions and overall environmental impact, have become increasingly important factors in business decisions. However, traditional decision support tools such as simulation have primarily focused on the operational aspects of industrial and service systems such as efficiency, productivity, and cost with little attention given to environmental impact. To address this issue, we have undertaken an effort to develop a sustainability toolkit for simulation. We plan to supplement the traditional constructs and performance measures that are provided in current simulation packages with a sustainability toolkit that will contain a flexible framework to enable the modeling and analysis of sustainability-related factors and performance measures. This toolkit is intended to be designed for ease of implementation, so decision-makers can have sustainability measures as readily available as traditional performance measures when making logistics decisions. In this paper, we outline the general methodology for the development of the sustainability simulation toolkit, and we demonstrate a very limited scope prototype with application to logistics and transportation systems.

2 SUSTAINABILITY IN LOGISTICS AND TRANSPORTATION SYSTEMS

For many companies, logistics and transportation can be one of the largest components of energy consumption and the overall emissions of the company. As such, sustainable logistics and transportation systems will be needed to improve the environmental footprint of companies. Traditional methods used for logistics and transportation decisions are primarily based on trade-off analyses of time, distance, and cost. The body of literature that is emerging in the area of sustainability, shows that there is a need to address impacts in all stages of a lifecycle in products or services. The goal of this paper is to present our preliminary investigation and the modeling and analysis methods developed for logistics and transportation systems that will integrate energy consumption, carbon emissions (such as CO and CO₂), pollutants (such as NO_x), and total hydrocarbon (THC) emissions along with the traditional aspects of time, distance, cost, and service level for making long-term and short-term logistics and transportation decisions.

Simulation modeling has been used in the context of logistics and transportation related to sustainability. Cortes et al. (2008) utilize simulation to estimate energy consumption and emissions for transportation networks in urban and rural areas over time horizons on the order of 10 years. In addition, Barth et al. (1999) analyze the shared vehicle systems and their resulting emissions using a simulation model. Lee (2000) constructs a dynamic network model to study the impact of traffic flow control on carbon dioxide emissions of passenger cars. In each of these cases, specialized models are designed for a spe-

cific purpose requiring significant time and effort. Wohlgemuth et al. (2006) develop a set of simulation plug-ins to be used in conjunction with a material flow analysis software that enables dynamic simulation of material flow and provides calculations of environmental performance measures such as emissions.

Given the increased focus on sustainability, there is a need to develop a flexible framework for efficiently modeling and analyzing systems that include sustainability performance measures in addition to performance measures that are traditionally collected such as work in process, time in system, utilization, and cost. Thus, the main objectives of this research are to:

- Create a sustainability toolkit that can be integrated into existing simulation software for the modeling and analysis of sustainability aspects of logistics systems;
- Implement the sustainability toolkit into a flexible framework for integration into off-the-shelf and customized simulation software;
- Identify and implement current models, relationships, and performance measures (e.g. truck energy consumption and emissions as a function of load profile, fuel type, velocity profile, and engine horsepower, among others) into the toolkit in a flexible structure that allows for user-specified changes and updates; and
- Conduct verification, validation, and testing of the sustainability toolkit for application to industrial logistics analysis and decision making.

The remainder of the paper is organized as follows. In the Section 3, we present the general methodology that we have developed for the design and implementation of the sustainability simulation toolkit. In section 4, we present the methodology implemented in the general application of discrete-event simulation to the logistics and transportation problem. In Section 5, we present the implementation of the prototype simulation tools using the ARENA simulation software. In Section 6, we give some conclusions and our plan for future work.

3 GENERAL METHODOLOGY

The general methodology for developing the sustainability simulation toolkit involves the following steps:

- Identify the sustainability factors and environmental impact performance measures for systems of interest;
- Establish simulation state variables to represent the sustainability factors and performance measures;
- Identify the events in the system that cause changes to the state variables, and translate these system events to simulation events and the associated event triggers;
- Establish the mathematical, statistical, and logical relationships among the state variables to update and change the values of the state variables as events occur in the system over time;
- Implement state variables, relationships, and events into a robust, flexible simulation toolkit modules; and
- Perform verification, validation, and testing of the simulation toolkit modules.

The first step of the methodology involves identifying, through the use of observation, studies, and domain experts, the sustainability factors and environmental impact performance measures for various systems of interest. Once the sustainability factors and performance measures have been identified, the next step is to determine how these factors and performance measures can be represented as state variables in the simulation model. Since we are utilizing discrete-event simulation, the changes to the state-variables will occur upon the instantaneous occurrence of events. For items such as emissions which may occur continuously over an interval of time, we will assume (at least initially) that emission quantity between event occurrences can be represented as a function of time, a probability distribution, or a stochastic process. In the future, it may be necessary to represent some factors as continuous variables with respect to time and utilize difference and/or differential equations to accurately represent some systems. Once the events causing changes to state-variables are identified and represented, their relationships and performance measures must be established. There are a number of published scientific studies that contain this type of information for various systems including sources such as the EPA, among others. Upon determining the mathematical, statistical, and logical relationships among state-variables, they are implemented into the sustainability toolkit consisting of a flexible framework of modules which are developed for integration into off-the-shelf and customized simulation software. Initially, this will take the form of implementing the modules in the ARENA simulation software. Upon gaining these capabilities our intention is to implement the modules in a general programming language such as C++ and provide “hooks” on the toolkit modules that will allow for easy adaptation to off-the-shelf simulation languages. In addition, we intend to construct the toolkit to allow easy and efficient user-specified changes, updates, and additions to the initial models and relationships.

4 METHODOLOGY APPLIED TO A LOGISTICS AND TRANSPORTATION PROBLEM

In this section, we present the sustainability simulation toolkit development methodology applied to logistics and transportation problems. In particular, our objective is to enable the simulation modeling and analysis of delivery and routing problems in order to evaluate sustainability factors and environmental impact performance measures including energy consumption and vehicle emissions. The following example illustrates the type of system under consideration.

Example: *Suppose a company has a centralized warehouse facility from which it makes deliveries to customers on a daily basis. The company currently has 8 trucks that consume diesel fuel. Each day routes are assigned to trucks. The route may consist of a variable number of delivery stops at customers and variable route distances that can each be represented by a probability distribution. The company is currently in a position where it needs replace part of its fleet of trucks. The company wants to determine the number and type of trucks to purchase (e.g. capacity, type of fuel, and engine power) while taking into account the energy consumption and emissions in addition to traditional system performance measures such as cost and customer service level.*

This example depicts a system where simulation could be the most appropriate tool to evaluate various alternatives in order to make a good decision. However, currently simulation software does not typically provide modeling and analysis tools to efficiently conduct such a simulation analysis.

For this type of logistics and transportation system, the primary source of energy consumption and emissions are due to the trucks. Thus, a truck will be represented by an entity in the simulation model which flows through the system and controls the delivery process. As fuel is consumed, emissions are produced. Manicom et al. (1993) conducted a study on the emissions produced by trucks of varying horsepower consuming diesel and four variations of biodiesel. These emissions consist of gaseous residues including carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x) and total hydrocarbon (THC).

The simulation model consists of two types of events, the arrival of a truck and the departure of a truck. When a truck leaves a customer, it starts to emit emissions and particulates and causes changes to the system state. When a truck arrives at a customer, it may be left idling during the delivery process based on some user-defined probability. If the truck is left idling, it continues to generate the emissions. However, if the truck is turned off, it stops generating emissions. In both cases, the system waits until the occurrence of the next event to change the system state and record accumulated emissions.

The quantity of emissions generated from burning the fuel is a function of several parameters including the type of the fuel, the truck engine horsepower, and the time that the engine is running (Manicom et al. 1993). The results of this research study provide a list of emission coefficients in the unit of grams per horsepower per hour (grams/hp · hr) for various fuel types including diesel, and 10%, 20%, 30%, and 40% soya blend biodiesel. Thus, we have the relationships:

$$f_Y(t) = C_{Y,Z}ht$$

where the emissions produced f of emission component Y over time interval t is equal to the emission coefficient $C_{Y,Z}$ for emission component Y given fuel type Z times the truck horsepower h times the time period length. This relationship can be used directly when the truck is idling, however when the truck is traveling between locations, the time component can be calculated as the distance traveled d divided by the average speed s resulting in the following relationship:

$$f_Y(t) = \frac{C_{Y,Z}hd}{s}.$$

As a typical transportation problem, traditional system performance measures include the average delivery time for each truck, total number of deliveries, and the service level for each customer. Some of these system performance measures may be collected by each individual truck (e.g. average delivery time for one truck), while some of them are accumulated for the whole system (e.g. total amount of deliveries). In addition to these traditional performance measures, the environmental performance measures, which include the amount of the various emissions emitted and the amount of fuel consumed, are collected. Similarly, environmental performance measures are collected for each truck and accumulated for all trucks to return performance measures for the entire system.

To illustrate the development of the modules that will make up the sustainability simulation toolkit, in the next section we detail the implementation of a set of prototype modules using the ARENA simulation software.

5 IMPLEMENTATION OF A PROTOTYPE SUSTAINABILITY TOOLKIT IN ARENA

For the implementation of the prototype sustainability toolkit in ARENA, we have created a small set of modules utilizing the ARENA template developer tool. The modules are used in a drag-and-drop fashion and can be used directly with the flow-chart simulation modules provided with ARENA simulation software.

To better illustrate the implementation process, we provide some additional details to the example presented in the previous section. All trucks are created initially, sent out for work on a daily basis. Each of the trucks serves a set of customers every day. The truck is routed to the customer, delivers the products with the truck idling or turned off, moves to the next customer and eventually returns to the warehouse. Table 1 shows an example instance of the route schedule for eight trucks on a particular day. Figure 1 depicts this routing instance.

To model this logistics and transportation system, three modules have been created and make up the toolkit. These modules include the *Truck Creation* module, the *Station with Emissions* module, and the *Route with Emissions* module. Figure 2 displays the *Emission Module* template panel (left side) and an overview of the simulation model for using the modules along with standard ARENA modules to represent the system defined in the example.

Table 1: Generated Instance of the Route Schedule

	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6	Truck 7	Truck 8
Route Distance	121.6	26.6	72.8	46.8	96.9	24.0	34.6	26.5
Number of Customers	3	9	9	8	1	4	6	10

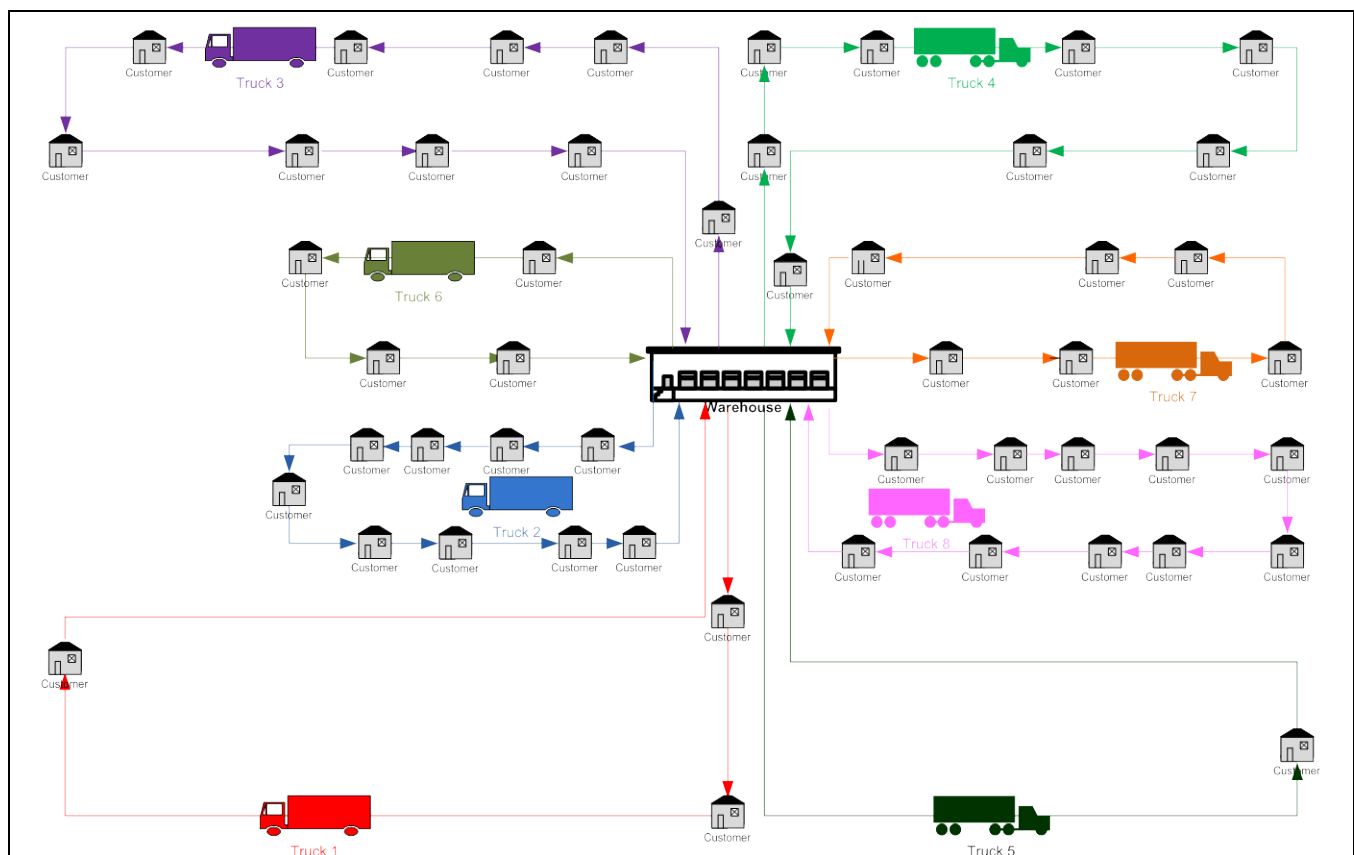


Figure 1: Diagram of a Sample Instance of Truck Routings Generated via the Example Simulation Model

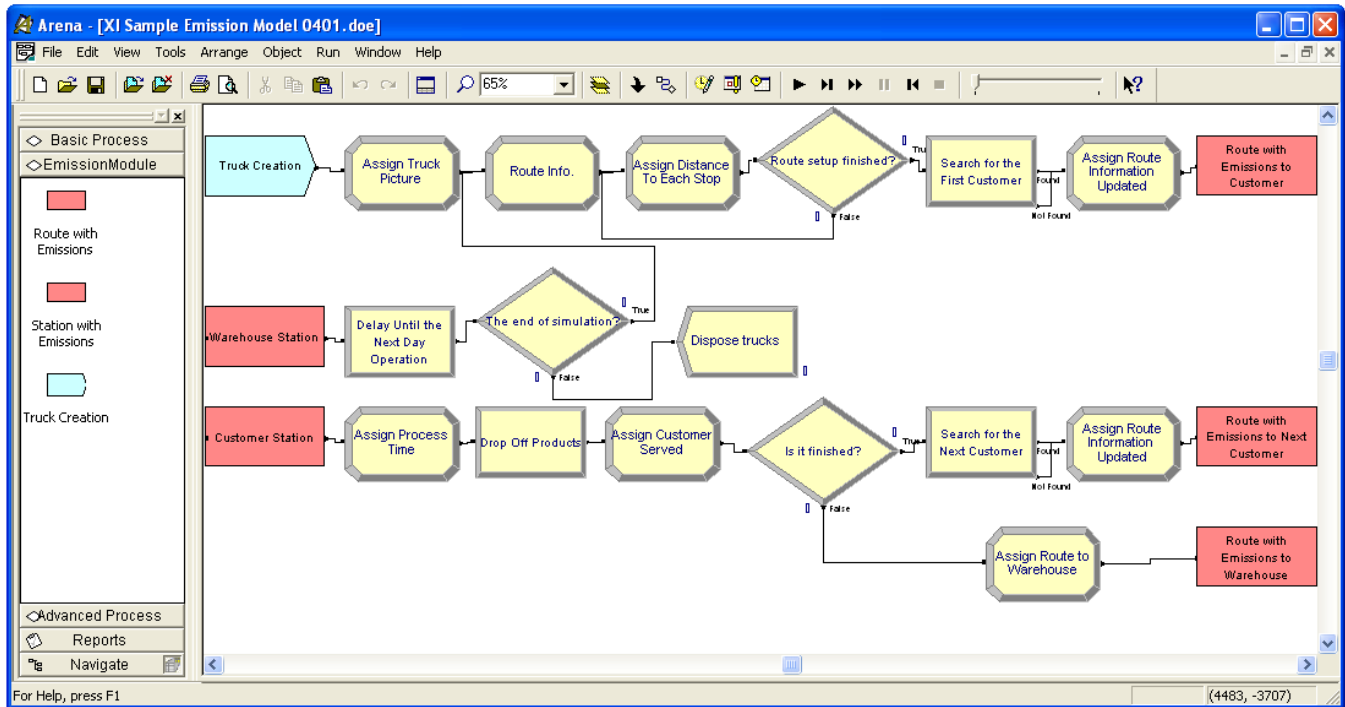


Figure 2: Example Simulation Model with Emissions Template (left side) Implemented in ARENA

In the *Truck Creation* module (see dialogue box in Figure 3(a)), the user is asked to provide the general information for the trucks, which includes the truck engine horsepower, the truck efficiency (measured in miles per gallon), the average speed of the truck and the fuel capacity. The user chooses the fuel type for the trucks to use. There are five types of fuel provided by our model, including the diesel, 10% soya blend biodiesel (B10), 20% soya blend biodiesel (B20), 30% soya blend biodiesel (B30) and 40% soya blend biodiesel (B40). Among four available emissions (CO, CO₂, NO_x, THC), the user may select which emission components they are interested in collecting. By checking the checkbox of emission types, the model will return the amount of emissions emitted by each individual truck and the cumulative amount of emissions produced by all of the trucks in the system.

The *Station with Emissions* module (see dialogue box in Figure 3(b)) provides the same functionality (representing a physical location) as a Station module in the ARENA. Additionally, when trucks arrive at a customer, which is modeled as a Station, our *Station with Emissions* module collects the emissions generated along the route from the location of the previous customer. The module accumulates the system emissions as well. Finally, the user can specify the probability of the truck idling while it remains at the station location.

The *Route with Emissions* module (see dialogue box in Figure 3(c)) provides the functionality of the Route module in ARENA and also calculates accumulating emissions while the truck remains at the station. It is used to route the truck to the next customer after the truck leaves the current location. The module provides two options to the user for entering the route information. The user can provide the route distance or the route time. The system cumulative emissions are updated in this module as well.

Given these toolkit modules, we utilize them along with standard ARENA modules to represent the system in the example. Referring to Figure 2, the *Truck Creation* module is used to create 8 trucks and enter their specifications. The routings for this example are specified in the assign modules. The first *Route with Emissions* module (labeled Route with Emissions to Customer) is used to specify the routing of the truck from the warehouse to the first customer. The *Station with Emission* module (labeled Customer Station) represents the location of “generic” customer. At each customer location, a process is used to represent the delivery process. The Decide module is used to determine if the route has been complete. If so, the *Route with Emissions* module (labeled Route with Emissions to Warehouse) is used to route the truck back to the warehouse. If the route is not complete, the *Route with Emissions* module (labeled Route with Emissions to Next Customer) is used to send the truck to the next customer on the route. The simulation model is set up to represent a simulation length of a 5 day week. Table 2 shows the specification of the parameters used in the simulation model.

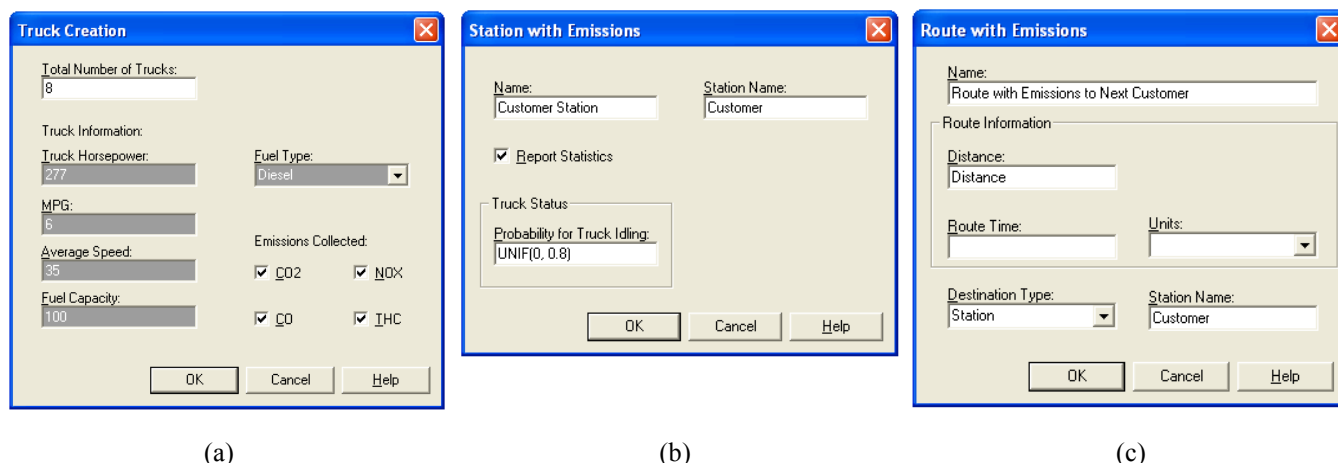


Figure 3: Simulation Module Dialogue Boxes: (a) Truck Creation Module, (b) Station with Emissions Module, and (c) Route with Emissions Module

Table 2: Simulation Parameter Specifications

Specification	Assigned Value
Number of Trucks	8 Trucks
Truck Horsepower	277 Horsepower
Truck Fuel Economy	6 Miles per Gallon
Truck Average Speed	35 Miles per Hour
Truck Fuel Capacity	100 Gallons
Fuel Type	20% Soya Blend Biodiesel
Route Distance	$22 + 275 \times \text{BETA}(0.896, 2.77)$ Miles
Number of Customers	Random Integer between 1 and 10
Probability for Truck Idling	Random Number between 0 and 1
Number of Product Boxes Unloaded	Random Integer between 1 and 10
Unloading Time	2 Minutes per Box

To demonstrate the use of the simulation model, the model was set up and run. Table 3 shows the output of the simulation model including both the environmental performance measures and the traditional system performance measures for the model run for one replication of 5 days using 8 trucks utilizing 20% soya blend biodiesel. The performance measures are collected and shown for each truck and for the entire system.

Table 3: Example of Simulation Results for Trucks using 20% Soya Blend Biodiesel over 5 Days

	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6	Truck 7	Truck 8	System
CO Emissions (gram)	8,276.2	2,650.5	5,442.2	5,021.6	4,728.0	5,877.8	5,724.4	6,286.3	44,007.0
CO ₂ Emissions (gram)	4.1E+6	1.3E+6	2.7E+6	2.5E+6	2.4E+6	2.9E+6	2.8E+6	3.1E+6	2.2E+7
NO _x Emissions (gram)	2.8E+4	9.0E+3	1.8E+4	1.7E+4	1.6E+4	2.0E+4	1.9E+4	2.1E+4	1.5E+5
THC Emissions (gram)	3,511.1	1,124.4	2,308.8	2,130.3	2,005.8	2,493.6	2,428.5	2,666.9	18,669.0
Route Distance (mile)	703.6	198.9	401.9	381.5	384.9	492.6	482.6	532.9	3,579.0
Route Time (hour)	25.2	8.8	17.1	17.8	14.5	18.6	19.1	19.7	140.9
Fuel Consumed (gallon)	117.3	33.1	67.0	63.6	64.2	82.1	80.4	88.8	596.5
Customers Served	28.0	18.0	34.0	40.0	18.0	24.0	29.0	30.0	221.0

To illustrate the comparison of alternative system configurations, the model was set up to compare the trucks using diesel fuel compares with trucks using 20% soya blend biodiesel. In order to compare the differences in performance measures using different types of fuel, we ran the simulation model 50 replications of one week (5 days) and compare the output performance measures. The data has been used to construct 95% confidence intervals on the mean value for each performance measure. Table 4 shows the comparison of the results.

The modules presented have been tested and verified with respect to the results of the emissions study by Manicom et al. (1993). Validation of the output of the simulation with respect to an actual system is part of our ongoing research process.

Table 4: Example Comparison of 95% Confidence Intervals on System Performance Measures

	20% Soya Blend Biodiesel		Diesel	
	Average	Half-width	Average	Half-width
System CO Emissions	44,612.0	1,165.3	51,034.0	1,333.0
System CO ₂ Emissions	2.2E+7	5.8E+5	2.2E+7	5.8E+5
System NO _x Emissions	1.5E+5	3.9E+3	1.9E+4	1.3E+3
System THC Emissions	18,926.0	494.4	24,334.0	635.6
System Route Distance	3,581.1	110.9	3,581.1	110.9
System Route Time	142.1	3.5	142.1	3.5
System Fuel Consumed	596.9	18.5	596.9	18.5

6 CONCLUSIONS AND FUTURE WORK

In this paper, we have introduced the effort that we have undertaken to develop a sustainability simulation toolkit. We have outlined the methodology for developing such a toolkit and demonstrated the development of prototype toolkit modules with application to a general logistics and transportation problem. From this prototype, we have shown the benefit that can be provided to simulation researchers and practitioners interested in including sustainability and environmental impact performance measures an integral part of the decision making process.

It is our intention to continue the development of the sustainability simulation toolkit to a wide variety of applications and domains where sustainability plays a critical role in operational decisions. We further plan to develop a more generalized framework to enable the inclusion of the simulation toolkit in customized and off-the-shelf simulation software.

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