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DISCRETE EVENT SIMULATION OF GREEN SUPPLY CHAIN WITH TRAFFIC CONGESTION FACTOR

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ABSTRACT

Reduction of Carbon-Dioxide (CO_2) emission has been a global challenge in strategic supply-chain decision making for many companies. This paper focuses on the transportation sector of the supply chain since it is a significant contributor to CO_2 emissions. To reduce CO_2 emissions, previous studies have focused on mathematical models, government policies that affect CO_2 emission and optimizing results. This article will focus on the impact of traffic congestion on CO_2 emission by means of simulating vehicle movement on the roads. A design of experiments was created in which thirty-two scenarios were tested using ARENA. The experiment focused on factors such as synchronization or desynchronization of traffic lights, mode of dispatch rates, and route configurations. Results revealed that the synchronization of traffic lights at each junction and the distribution of dispatched trucks would increase the amount of CO_2 emissions significantly.

1 INTRODUCTION

A Supply chain is a system of activity that involves the flow of resources and information, along with a product or service (Perea et al. 2000). It is concerned with transforming raw materials, natural resources, and other key components into a finished product or service. In today's context, the supply chain is very dynamic, competitive, and complex (Harland, Brenchley, and Walker 2003). Strategic decisions encompassing planning and coordination among different departments, like manufacturing, logistics, procurement, sourcing and retail operations, necessitate cost flow analysis, resource allocation, and scheduling. In addition to these complexities, climate change concerns(Karl and Trenberth 2003), government policies on greenhouse gas emissions, and energy consumption reduction are increasingly becoming a global challenge discussed on the world stage. Logistics processes of inbound-outbound freight movements have been seen as a major contributor to greenhouse gas emissions, especially Carbon-DiOxide emissions, although the impact of other gasses is also detrimental to the environment. This paper considers transportation as a significant greenhouse-gas emitting sector, and focuses on how companies can make certain logistical decisions which will have a positive impact on the environment.

The concepts of Green Logistics (Murphy and Poist 2000, Murphy, Poist, and Braunschweig 1996, Srivastava 2007) are becoming increasingly important for achieving the reduction of CO_2 on a global scale. Government regulations, carbon-tax policies, and pressure from consumers and environmental groups have proved to be key catalysts in redesigning or restructuring the supply chain for many companies (Wu and Dunn 1995). This ultimately affects many managerial decisions concerning trade-offs between cost and environment (Ebinger, Goldbach, and Schneidewind 2006). For such complex strategic decision-making, discrete event simulation (DES) can be used as a tool for designing green and cost-effective supply chain simultaneously (Rabe et al. 2015).

This paper discusses integrating important supply chain performance indicators such as the number of dispatches of trucks, travel time, and CO_2 emission factors into a single model which simulates traffic congestion on transportation routes. Thirty two scenarios have been simulated based on vehicle dispatch schedule, traffic light synchronization or desynchronization, and route configuration.

2 LITERATURE REVIEW

2.1 Green Supply Chain

In today's world, concern for the environment is leading many manufacturing companies to address the size of their carbon footprint by measuring and reducing their emission levels. To make this happen, these industries are focusing primarily on designing a green supply chain (Beamon 1999). However, developing an efficient network and logistics process and creating value for customers are also important concerns for these companies. To achieve all of these goals simultaneously, they are creating value in the supply chain network which reduces the cost of the product, improves delivery service, and reduces the time of delivery. Previous studies, like Sundarakani et al. (2010) have contributed to this goal by introducing the practice of green supply chain management. They proposed a method for measuring and controlling the carbon footprint across the supply chain.

Ubeda, Arcelus, and Faulin (2011) studied the decisions made at the operational level to reduce the environmental impact of transport activities in the Eroski Group. They discussed ways to optimize Eroski's fleet efficiency and examined the impact of those practices on the profitability of its operations and on the environment. This was followed by a description of a methodology to design green transport routes.

Fareeduddin et al. (2015) stated that regulatory policies should be considered when constructing a green closed-loop supply chain model: strict carbon caps, carbon taxes, and carbon cap-and-trade systems. Previously, supply chain models were formulated as unidirectional models, not considering the reverse activities of customers such as returning products. Fareeduddin et al. (2015) proposed optimization models for a closed-loop supply chain that consider economic and environmental aspects, decision-making and carbon regulatory policies.

Wang, Lai, and Shi (2011) provided a multi-objective mixed-integer programming(MIP) formulation for the supply chain design phase, which they claim is the first model that considers the investment decision in the supply chain design. They applied the normalized normal constraint method which finds and distributes the Pareto optimal solution so the result can be easily applied in the decision-making system. Finally, they conducted a comprehensive set of numerical studies on the Pareto solutions, especially on the sensitive parameters, in order to attain useful managerial insights. The results obtained from all these studies give insight on decision-making at different levels of the supply chain which in turn contributes towards establishing key performance indicators as well as environmental parameters.

2.2 Models to Reduce CO_2 Emissions in the Green Supply Chain

People worldwide are raising concerns over the increase of energy consumption. But on the other hand, they wish for a versatile supply of products in a responsive manner. Such issues makes supply chain modeling difficult and achieving green supply chain goals harder. Studies like the one presented by Gross, Hayden, and Butz (2012) have explored the indirect effects of the price of oil on the ecological footprint of the network through the amount of CO_2 emissions. Rabe et al. (2015) have illustrated that moving trucks can be considered as moving warehouses and that CO_2 emissions are proportional to the period of storage.

Another study by Harris et al. (2011) explored the relationship between total logistics costs and environmental impact. By including the environmental factor, they have provided new insights on supply chain structure (number of facilities) and vehicle utilization ratios. The analysis revealed that cost-based optimum design does not necessarily fulfill CO_2 emission reduction objectives.

Elhedhli and Merrick (2012) developed a green supply chain design models that incorporates the cost of carbon into the objective function, with the goal of minimizing logistics cost and CO_2 emissions. They specified two contributions: one is a solution model based on Lagrangian relaxation which can be used to solve the resulting concave minimizing problem; the second is the positive impact that the consideration of carbon emissions in the decision-making process provides in determining the optimal configuration of the network.

Urata et al. (2015) developed a MIP method to determine market demand as well as a reduction ratio of environmental impact by identifying supplier and factory locations between developed and emerging countries. A previous model had been created which considered CO_2 volumes by using Life Cycle Inventory (LCI) databases in China and Japan. However, its effectiveness was under question since it was not easy to do unified evaluations with different databases.

Several strategic decisions regarding technology selection, inventory levels, transport modes, facility location, and resource allocation were evaluated integrating carbon abatement and different carbon policies (Marti, Tancrez, and Seifert 2015). Similarly Benjaafar, Li, and Daskin (2013) demonstrated in another study that carbon emissions can be reduced without significantly increasing operational cost. They also analyzed the impact of different carbon policies on supply-chain management decisions. Abdallah et al. (2012) developed an MIP that focuses on minimizing emissions throughout the supply chain by considering environmental sourcing. In addition, they presented a case study which illustrated life cycle assessment founded upon the costs of different carbon emissions. Reviewing all this papers, we conclude that many approaches have been made to reduce CO_2 emissions by deriving mathematical models and optimization techniques that focus on pinpointing the location of the facilities, the number of dispatches according to demand, and transportation modes.

A limited amount of study has emphasized the impact of traffic congestion, route configuration, or dispatch time on CO_2 emissions and has modeled this in a discrete event simulation model. Even though Barth and Boriboonsomsin (2008) illustrated that CO_2 emission reduction is possible if strategies like vehicle flow at better speeds, agreement techniques and shockwave suppression techniques are considered, DES model approach was not considered. But Rabe et al. (2012) emphasized the use of discrete event simulation techniques to evaluate green supply chains.

2.3 Traffic Congestion

A traffic congestion phenomenon can be defined as the instability and phase deviation of a dynamic traffic flow system which is triggered by a small disturbance without a specific reason such as a traffic signal or traffic accident (Bando et al. 1995a). Developing a traffic model requires taking into account several factors such as movement of vehicles or traffic flow, traffic signals, and legal regulations related to distance and velocity (Bando et al. 1995b). Burghout, Koutsopoulos, and Andreasson (2006) highlighted different types of traffic simulation models and presented the idea of combining features from mesoscopic models and microscopic models to create a hybrid traffic simulation model. Jun (2009) studied congestion percentage as well as duration based on real data and proposed a measure for describing the severity of traffic.

Our proposed model of traffic congestion takes into consideration different factors such as traffic light synchronization or desynchronization, route configuration, distribution of dispatched trucks throughout a day, etc. These factors have generated a total of thirty-two scenarios which were modeled using discrete event simulation. The features included in the simulation model consider factors related to mesoscopic traffic models.

3 METHODOLOGY

3.1 Conceptual Model

We began with a conceptual model depicting the impact of traffic congestion on carbon dioxide emissions. Traffic congestion is most likely to occur due to the high arrival rates of the vehicles at an intersection point where more than two roads cross thus creating branches of roads. Each intersection point is equipped with traffic lights which control the movement and the direction of the incoming traffic. The conceptual model illustrated in Figure 1 considers different routes based on the state of the traffic lights and the congestion of the roads.

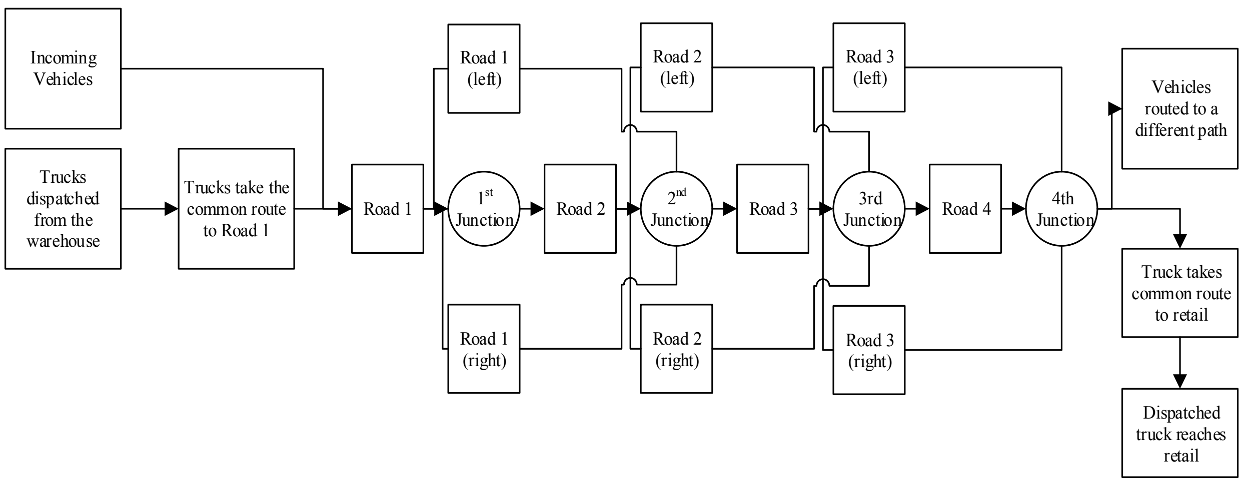

Figure 1: Conceptual Model of Traffic Network.

The conceptual model illustrates that dispatched trucks start from a warehouse, move through four junction points and finally reach the destination (the retail store). At each junction, all the vehicles can go left or right based on the availability of the road space ahead or the availability of a green traffic light. As we focus on the trucks which have been dispatched from the warehouse bound for retail stores, all other vehicles are routed out of the conceptual model through another route.

3.2 Model Assumptions

The following assumptions were made in developing the conceptual model of traffic congestion into a discrete event simulation model:

- At every intersection, three routes were considered, a straight route, a left and a right route. The left and right routes of an intersection always merged at the next intersection. The branch routes originating from the left and right routes were beyond the scope of this paper.
- Each route had a single lane.
- The flow of all vehicles was unidirectional; no vehicle could travel in the reverse direction.
- All delays associated with vehicles were due to congestion. No other delay cause, such as vehicle breakdown, failure, or idling was considered in this study.
- Since the flow of the vehicles was unidirectional, at each intersection there were three traffic signal post system. For each traffic signal post, only the red light and green light state were considered.
- At each intersection, only one traffic light was green at any given time.

- When the traffic lights were synchronized, the time in between a red light and a green light was set at 45 seconds. But when the traffic lights were not synchronized, the time in between a red light and a green light was presented as an expression of uniform distribution (40,50) .
- The space in the middle of each junction could not be blocked by vehicles. All vehicles stopped behind the line at the junction.
- The hourly arrival rates of all the other vehicles except the dispatched trucks were assumed to be constant throughout the simulation run.
- The trucks dispatched from the warehouse were heavy-duty vehicles, traveling at 55 mph.
- The space availed by a truck or any other vehicle were considered to be the same dimension.
- The distance for the long road between each junction was assumed to be two times the distance of the short road between each junction with the same process time, with a total of three blocks for the short distance and six blocks for the long distance.

3.3 Simulation Model

In order to develop a discrete event simulation model for traffic congestion, this study used ARENA (v.14.7) simulation software. With the different features embedded in the ARENA simulation software, it was possible to simulate different scenarios into the Design of Experiment section which will be discussed. That being said, this section will discuss how the conceptual model was developed into the DES model. The simulated traffic congestion model in this article contains four key elements that constructs this model.

3.3.1 Roads as Resources

In this study, roads were considered as resources with a processing time. The roads were subdivided into small chunks which could be occupied by a truck or an incoming vehicle. Each of these small chunks were considered as a resource with a small delay time. Whenever a vehicle seized one of these resources, it began the process of following a route and could or could not seize the next chunk of road based on its availability. Figure 2 illustrates the basic building blocks of the road and the simulated concept of how vehicles occupy space.

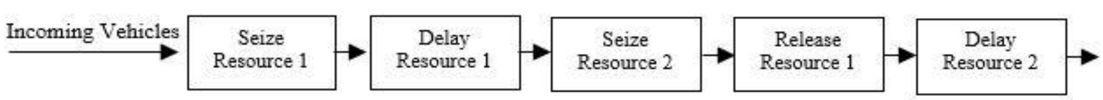

Figure 2: Simulated Model of Roads.

3.3.2 Junctions

In this paper, four junctions or intersections were considered. Based on our assumption of the unidirectional flow of the incoming vehicles and the different routes originating from an intersection, three traffic lights (TL) were created at each junction. Figure 3 illustrates how an intersection was conceptualized in our simulation model. In the figure, sections 1.1, 1.2, 2.1, 2.2, and so forth are considered small chunks of resources which can be seized by only one vehicle at a time.

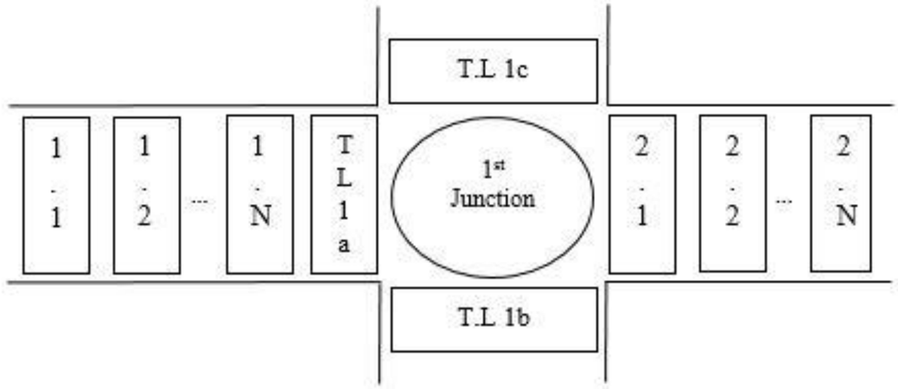

Figure 3: Junctions and Traffic Light System Positioning.

3.3.3 Deciding Routes

In the model, as vehicles arrived at an intersection, the movement of the vehicles was controlled by the traffic lights and the availability of the road ahead. The availability of a traffic light was given preference for making the decision of which way to go in an intersection. The traffic light was considered available when it was green. If a traffic light was not available or the space in front of the vehicle was occupied (seized by another entity) the vehicle was supposed to look for the availability of other traffic lights and take that route-immediately. Figure 4 shows the decision modules as they were arranged in the simulation. To summarize, the vehicles were to first look for the availability of the traffic light going straight, then for traffic lights to go right and finally for traffic lights to go left.

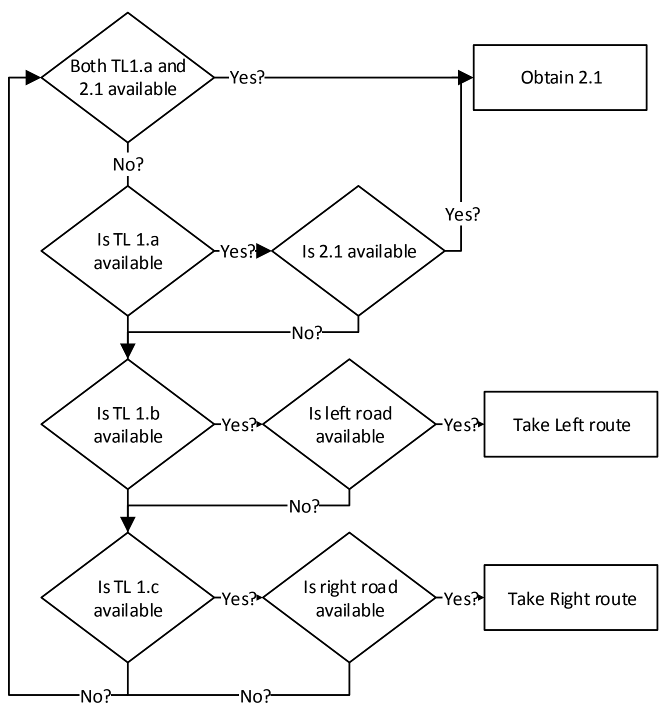

Figure 4: Decision Modules at Intersection.

3.3.4 Traffic Lights (TL)

Based on our assumption that there would only be two states of a traffic light (red & green), a separate model was used to generate these two required states. Since traffic lights were considered as resources, whenever there was a green light in one of the lights at an intersection, the other two traffic lights for that intersection were red. This was done in a cyclic manner, using a logical entity to create red lights and green lights for all three TL at each intersection. Figure 5 illustrates the fact that a single entity, a pulse, was created and looped through all processes during the simulation run time, while the TL are being processed they have been given high priority.

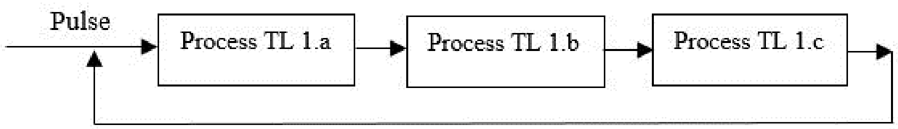

Figure 5: Generating Traffic Light Availability.

4 DESIGN AND ANALYSIS OF EXPERIMENT

4.1 Traffic Congestion Factors & Scenario Construction

Using the traffic congestion simulation approach, different cases and scenarios were developed to study the relationship between CO_2 emission and traffic congestion. The design of experiment was constructed with factors having 2 different levels. For the two different levels of the traffic lights synchronization, a value of 45 seconds was taken when all lights were synchronized and desynchronized when all lights followed a Uniform distribution of (40,50) seconds. Another factor that was considered in the design of experiment was truck distribution. The distribution of the trucks varied, based on 1) peak hour values, where the peak hour was between 12 pm to 1 pm and 6:00 pm to 8:00 pm; or 2) flat distribution, where the truck was distributed for the whole day at the same value, a ratio of one entity per hour. The peak hour values used a normal distribution for the arrival rates of the trucks centered around the peak times. The flat distribution used a constant rate throughout the day." The third factor considered in this experiment analysis, the most critical factor, was the road distance. Road distance only accounted for the three roads possible between the intersections and were valued as either short or long sections. The combinations of all of these factors in the DOE analysis showed that 32 scenarios in full factorial experimental design with 2 different levels in each factor would have to be considered. Created with a JMP 10.0 statistical program, Table 1 shows the factorial levels considered.

Table 1: Traffic Congestion Factors.

Factors	Level	
	High(+)	Low(-)
Road 1 Distance	Long	Short
Road 2 Distance	Long	Short
Road 3 Distance	Long	Short
Synchronized Traffic Lights	Yes	No
Schedule Truck Type	Normal Distribution (Peak Hours)	Uniform Distribution (throughout the day)

4.2 CO_2 Emission Calculations

The results from the traffic congestion simulation runs in each scenario provided the total time required for trucks to reach the warehouse and it also recorded the number of trucks arrived to the warehouse. The simulation was run for 15000 minutes per replication with the assumption that the number of replications will give with 95% confidence, a half-width less or equal than 5% of the average time in the system. This resulted in running the model with 10 replications. The generated (total) time along with the number of trucks recorded for each scenario was recorded and multiplied with the CO_2 factor specified by the United States Environmental Protection Agency, updated for 2014 as shown in equation 1. As shown in equation 2, the emission factor for Heavy Duty Trucks (HDT) was taken in this model to be 1.456 kg/ vehicle-mile (Emission Factors for Greenhouse Gas Inventories, 2014). As the results of the simulated model offered the total time in the system for the dispatched trucks, the distance (from equation 2) was calculated by equation 3. For all the scenarios, the overall CO_2 emission was calculated with equation 2. The calculation for the emission factor is shown below:

$$CO_2\,Emission = Emission\ factor\ for\ HDT * Number\ of\ trucks\ reaching\ destination * Total\ distance\ driven \quad (1)$$

After simplification,

$$CO_2\,Emission\ (kg/no.\ of\ vehicle\ miles) = 1.456 * Number\ of\ trucks * Distance\ (miles) \quad (2)$$

$$Total\ Distance\ of\ truck\ (miles) = Speed * Time = 55\ miles/hr * Total\ truck\ time\ from\ simulation\ run \quad (3)$$

5 RESULTS

5.1 Statistical Analysis

CO_2 emission values were put into JMP statistical software (version 10.0) and the 32 scenarios were run in a full factorial experimental screening design to verify the significance of each factor. The significance of the combination of second order or higher order of interaction between the factors were considered from the DOE with a minimization goal. The results of the DOE statistical analysis screening are shown in Figure 6. The half normal quantile (X- axis) shows the main effect or interaction and its rank along with other main effect and interactions. The order estimate (Y-axis) helps to assess the factors that impacted the generated model according to their significance.

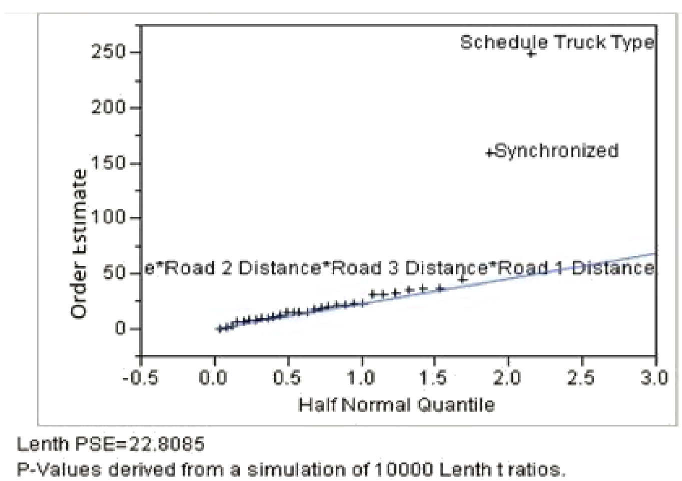

Figure 6: Screening Anlaysis in JMP 10.0.

The significant factors in the screening analysis of the statistical analysis were found to be the scheduling of the trucks and the synchronization factor. In addition, the combination of the three roads showed a significance level that must be considered in running the statistical analysis.

5.2 Prediction Profiler for Factors

The resulting total CO_2emission was then combined with the 32 scenarios to find the combinations that would generate the least amount of CO_2 emission. The recommended factors were run into a prediction profiler. It was done to check the maximum allowable conditions for each of the factors to make the CO_2 emission response as low as possible (maximizing the factors to produce the minimum possible CO_2 emission). The prediction profiler is shown in Figure 7.

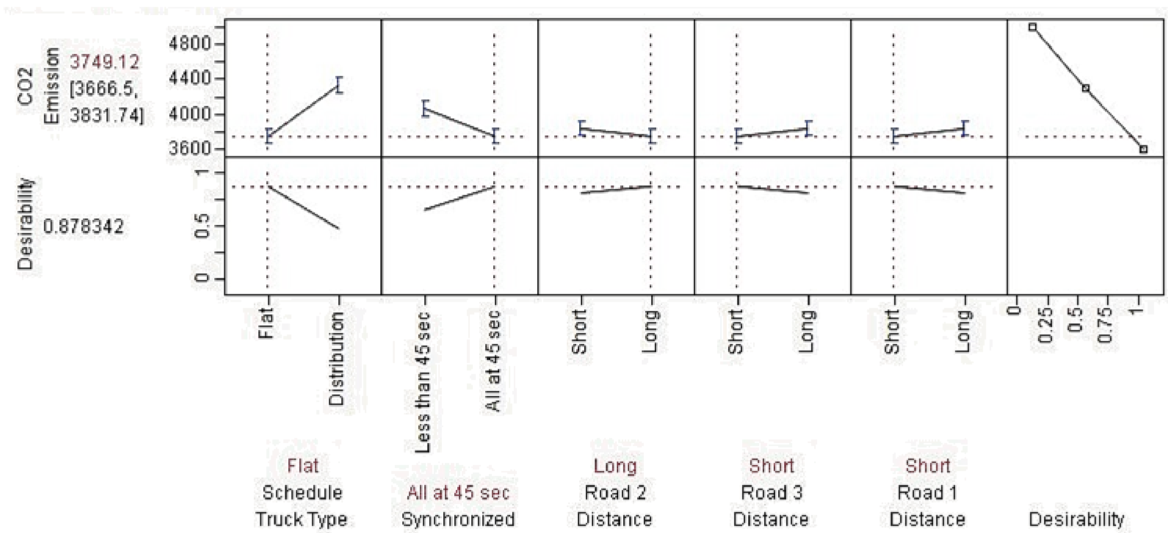

Figure 7: Prediction Profiler for Factors.

The prediction profiler analysis shows that the best way reduce the CO_2 emission level is by using flat scheduling for the trucks. This means that trucks need to be distributed throughout the day. Dispatching trucks during peak traffic hours is likely to increase CO_2 emission due to congestion. It is also visible that if the traffic lights are synchronized it creates positive impact on the environment. Finally, warehouses and truck drivers should be aware of the distances between the places of congestion (junctions) and when it is most efficient to use a combination of short – long – short distances between junctions to have the lowest emission factor possible. When the traffic lights are synchronized and red, chances are higher that the resources in road 3 (short) will be seized by vehicles. This causes queue buildup from road 3(short) to road 2(long). There are chances that, not all the resources in road 2(long) are seized due to its length. This impacts the vehicular movement in the road 1(short) when the lights turn green, chances are high that these vehicle will get more space in the road with less delay time for resource capturing.

In real life situation, the long distance roads regulate larger amount of vehicle movement during any instant due to its space advantage than short roads. When it is divided into smaller roads with traffic light system in junctions, the journey time increases along with waiting time.

6 CONCLUSIONS AND FUTURE RESEARCH

This study has taken a novel approach in understanding CO_2 emission based on the generation of a traffic congestion model. The methodology focused on the integration of DES, traffic congestion and CO_2 emissions, and design of experiments for generating multiple scenarios based on several factors in a conceptual model. Since this was only a conceptual model, it considered unidirectional (forward) flow of vehicles consistent to the one presented by Burghout, Koutsopoulos, and Andreasson (2006). Some of the limitations of the conceptual model include the fact that in general, vehicles move both forward and backward. In addition, no other vehicles enter the system from other directions especially in the junctions or intersections. This affects the overall generality and can have potential impact on total time a vehicle spends in the system and thus overall calculation.

Nevertheless, the intent of the research was to prove how simulation can be used to estimate the impact of congestion and the design of traffic patterns such as road length and traffic light synchronization on CO_2 emissions. For this reason, the arrival rates of vehicles and scheduled arrivals of trucks into the system was conceptualized and was taken constant throughout the simulation run. It also showed how variables related with schedules, road length and traffic system behavior can prove to be a critical factor in overall CO_2 emissions.

Based on the results of the conceptual model, it can be concluded that factors like synchronization or desynchronization of traffic lights, route configuration between origin and destination, and the pattern of dispatched vehicles (distribution of vehicles over the day) can have a significant impact on CO_2 emission. This study therefore shows that changes to any or all of these factors can impact CO_2 emission. The applicability of this model to real life scenarios may have even bigger impact if more factors are considered and assumptions are narrowed towards real life situations.

To test the conceptual model's generality, real data of hourly arrival rates of vehicles into a system can be provided by studying any transportation setting. This study can open up more opportunities in the field of simulation and mathematical modeling. Future research needs to focus on the following points:

- Addition of factors which impact CO_2 emission results, such as multi-directional vehicle movement and multiple lanes to generate more scenarios.
- Obtain further precision in the calculation of emissions during car acceleration and deceleration.
- Validation of the model with numerical data and implementation of the concept in a real life settings.
- Integration of more complex decision criteria to determine movement of the vehicles.
- Consideration of other continuous situations in addition to the velocity of the vehicles which will require much more sophisticated simulation software.
- Schedule of trucks dispatched from the service provider. This can be collected by studying the records provided by an actual service provider.
- Arrival rates of vehicles into intersections and into the system. In such cases, the overall system boundary needs to be redefined.
- The transition time between a red light and a green light can be obtained by collecting data on a real setting.
- Length of the roads can be thought of as small meshes. Each mesh can incorporate a certain number of vehicles which will depend on how the roads are being modeled. A certain road length with higher meshes will incorporate smaller number of vehicles in each one of them compared of smaller meshes will incorporate large number of vehicles in each one of them.

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