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An Integrated Approach for Promoting Sustainable Transportation: A Case Study of Fuel Consumption and Carbon Dioxide Emissions Reduction in the Cairo Transport Authority

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ABSTRACT

This research presents an integrated approach to address the Transportation Problem (TP) with a focus on minimizing fuel consumption and reducing carbon dioxide emissions, aimed at promoting sustainable development. The proposed solution combines mathematical modeling techniques and heuristic search algorithms, tailored to the specific context of the Cairo Transport Authority (CTA) transportation network in Egypt. The study demonstrates the effectiveness of this approach in achieving a balance between reducing fuel consumption and transportation costs while upholding service quality and customer satisfaction. Notably, the results highlight the significant potential for reducing carbon dioxide emissions by optimally allocating buses to routes, leading to an annual reduction of over 400,000 kg of emissions. These findings have important implications for transportation planning and management, emphasizing the benefits of adopting sustainable transportation solutions to mitigate the adverse environmental impacts of transportation.

***Keywords**: Transportation Problem, Linear Programming, Sustainable Development, Fuel Consumption, Carbon Dioxide Emissions, Cairo Transport Authority*

1 INTRODUCTION AND LITERATURE REVIEW

The transportation model is a critical field of study within the domain of linear Operation Research and Applied Mathematics, with a primary focus on the distribution of a commodity from several sources, such as factories, to multiple destinations, such as warehouses [1]. The primary objective of the transportation model is to determine the optimal shipping schedule that minimizes the overall shipping cost while adhering to supply and demand constraints.

According to Taylor and Patel et al., the transportation problem was first introduced by F.L. Hitchcock in 1941, who presented a study on "The Distribution of a Product from Several Sources to Numerous Localities." Hitchcock's research is widely recognized as the first major contribution towards addressing transportation problems. In 1947, T.C. Koopmans presented an independent study called "Optimum Utilization of the Transportation System," which further contributed to the development of transportation models involving multiple shipping sources and destinations [2].

The transportation problem (T.P.) is so named because many of its applications involve determining the optimal method for shipping goods. Typically, the solution to the transportation problem involves identifying an initial basic feasible solution for the T.P., testing the optimality of this solution, and moving towards optimality if necessary [3].

The T.P. deals with identifying the most efficient distribution of goods from various sources to different destinations, with the goal of reducing the overall transportation cost. The transportation problem is unique in nature among linear programming problems, as it involves finding the optimal distribution of a commodity from each source to each destination [4]. Sources can include delivery centers such as factories, while destinations can consist of receiving centers like warehouses. Each source can deliver multiple units of the product, referred to as capacity or availability, while each destination has its demand, known as the requirement [5].

Minimizing fuel consumption and reducing carbon dioxide emissions are essential steps towards promoting sustainable development in vehicles [6]. The transportation sector is a significant contributor to global carbon emissions, and the reduction of emissions from vehicles is imperative for achieving our global climate objectives[7]. The combustion of fossil fuels such as gasoline and diesel in vehicles releases carbon dioxide and other harmful pollutants into the atmosphere, which contributes to global warming and air pollution. These consequences have severe impacts on the environment and human health. Therefore, minimizing fuel consumption and reducing carbon dioxide emissions can help reduce our carbon footprint, mitigate the negative effects of climate change, and improve public health.

Additionally, promoting sustainable development in vehicles is crucial for reducing air pollution and improving public health. Vehicle emissions cause air pollution that can lead to respiratory diseases, heart diseases, and premature death, among other health problems. By minimizing fuel consumption and reducing carbon dioxide emissions, we can decrease the number of pollutants released into the air, resulting in a cleaner and healthier environment for all [8].

The importance of promoting sustainable development in vehicles lies in its ability to reduce our carbon footprint, mitigate the effects of climate change, and improve public health by minimizing air pollution. The transportation problem provides a framework for optimizing the distribution of goods, and by incorporating sustainability principles into transportation models, we can work towards achieving a more environmentally friendly and socially responsible transportation system.

In this paper, we address the pressing challenge of mitigating the environmental impact posed by urban transportation systems, focusing on the context of the Cairo Transport Authority (CTA). Through a novel integration of mathematical modeling techniques and heuristic search algorithms, we present a holistic solution to the Transportation Problem. By optimizing bus allocation and route selection, our approach aims to simultaneously minimize fuel consumption and carbon dioxide emissions. This research not only targets immediate resource efficiency objectives but also aligns with the broader aspiration of fostering sustainable urban development. By striking a balance between environmental considerations and maintaining service quality, our study underscores the potential benefits for transportation management and urban sustainability.

2 The General Structure of the Transportation Problem

The mathematical formula of the classical transportation problem is described as an equation:[9]

$$\text{Min. } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \qquad 1$$

Subject to:

$$\sum_{j=1}^{n} x_{ij} = a_i, i = 1, 2, \ldots, m; \qquad 2$$

$$\sum_{i=1}^{m} x_{ij} = b_j, j = 1, 2, \ldots, n; \qquad 3$$

$$x_{ij} \geq o \;\forall\; i \text{ and } j \qquad 4$$

In the given problem formulation, the notation C_{ij} represents the cost incurred for the transportation of a single unit of the commodity from a specific origin I to a designated destination j. The variable X_{ij} denotes the quantity of the commodity to be transported from the origin i to the destination j. Additionally, the parameter ai represents the available supply of the commodity at the origin i, while the parameter b_j represents the demand requirements of the commodity at the destination j.

While the total availabilities are equal to total requirements (i.e. $\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j$) then the transportation model is called balanced T.P.

3 FUEL EMISSION REDUCTION

Fuel emissions result from the combustion of fuel, and the amount of carbon dioxide produced is directly related to the energy output. The quantity of carbon dioxide generated during combustion depends on the amount of carbon in the fuel[10]. During the combustion process, the carbon atom in the fuel combines with two oxygen atoms in the air to form carbon dioxide. The molecular weight of carbon dioxide is 44, while the molecular weight of carbon is 12.

$C + O_2 = CO_2$

The calculation of carbon dioxide emissions is essential in environmental preservation. Carbon dioxide is a greenhouse gas, and reducing its concentration in the atmosphere can help preserve the environment and mitigate climate change[11]. For instance, to determine the amount of carbon dioxide emissions from diesel fuel, we can use the following conversion factors: 22.3562 lbs of CO_2 per gallon of diesel, 1 gallon = 3.78541178 L, and 1 lb = 0.45359 kg. Thus, 1 liter of diesel fuel produces 2.678835758 kg of CO_2 emissions. Given that the density of petroleum diesel is about 0.85 kg/L at normal conditions, we can calculate that 1 kg of diesel produces 3.1516 kg of CO_2 emissions.

4 CASE STUDY

The Cairo Transportation Authority (CTA) is a prominent and long-established transportation company in the Middle East, founded in 1966. According to the company's records, their fleet of 3,000 buses travels approximately 365,000 kilometers each day, serving around 1.5 million individuals in three governorates. The monthly fuel consumption of the fleet is approximately 6.5 million liters, costing approximately 40 million Egyptian pounds. Additionally, the maintenance and safety costs for this fleet amount to around 200 million pounds, with tire costs reaching approximately 70 million pounds annually.

The organization operates on two shifts: morning and afternoon. The first shift starts early in the morning when the buses travel from various garages owned by the company, where they are serviced and maintained, to the starting stations where they begin their daily journey. Each garage serves several buses, and the distances traveled by the vehicles from the garages to the start stations are non-efficient kilometers, resulting in significant fuel consumption with no income. The objective of this paper is to reduce these distances by redistributing the buses in their garages using a transportation method based on the primary objective of fuel consumption cost reduction. The optimal distribution will be generated based on the studied objective.

The collected data includes the number of garages in selected sectors, the number of starting stations, the capacity of buses in each garage, the capacity of buses in beginning bus stations, the distance between each garage and starting station, the current distribution of buses in their garages, and the average fuel consumption for buses according to their life.

The study in this paper focuses on four sectors out of seven sectors of the CTA existing in the three governorates. These sectors include 7 CTA garages and 22 beginning bus stations.

Due to the variation in the types and models of buses used in the company, the average fuel consumption varies for different types of buses. However, an average fuel consumption rate has been adopted for all types of buses in this study. Table (1) provides the distances in kilometers between each garage and each starting bus station. Table (2) illustrates the current distribution of buses.

5 ANALYSIS OF RESULTS

Upon solving the initial transportation problem and juxtaposing the optimal bus distribution against the company's prevailing allocation, a substantial inefficiency emerges, revealing a daily waste of 6341 kilometers in non-productive travel during the observed period. However, by adopting the proposed optimal distribution, this inefficiency could be curtailed to 5017 kilometers.

Further scrutiny exposes a daily fuel loss of 1841 liters within the current configuration, attributable to non-productive kilometers. This depletion would be ameliorated to 1428 liters per day upon implementing the optimized distribution. Furthermore, the average daily carbon dioxide emissions under the present circumstances stand at 4,932 kg, a metric poised to diminish to 3825 kg through optimal distribution, showcasing an enhancement of 22.44%.

It is imperative to underscore that executing the optimal distribution holds the potential to abate fuel emissions by an excess of 400,000 kg of carbon dioxide on an annual basis. These revelations resoundingly underscore the profound influence of judicious bus distribution optimization in waste reduction and the advancement of environmental sustainability, corroborating the pivotal tenets articulated in the preceding abstract and conclusion.

Table (3) presents the optimal allocation of buses to different routes, with the aim of minimizing fuel consumption.

Table (1) Distances between each garage and each starting bus station (Km).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
G1	17	14	13	17	16	24	14	16	19	15	18	3	4	8	13	6	9	16	13	17	8	12
G2	12	10	14	18	17	15	8	7	10	7	10	11	13	19	2	8	11	5	8	15	11	8
G3	18	15	13	17	13	23	16	18	22	18	20	4	7	13	15	7	2	17	12	16	9	12
G4	10	6	7	11	10	17	6	9	11	8	11	6	8	14	8	6	7	11	6	11	3	5
G5	16	13	11	15	8	22	12	15	17	13	16	9	12	22	14	10	8	18	11	15	7	10
G6	8	11	15	20	21	8	5	2	3	4	4	17	20	27	6	16	17	6	7	14	14	8
G7	6	8	12	16	15	11	4	3	7	3	7	13	15	23	3	12	13	7	4	13	9	6

Table (2) Current distribution of buses.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	ai
G1												16	5	20							7		48
G2							40								50	24			12				126
G3				21		19				24	16		10			23	75						188
G4												9				17					37	16	79
G5		27	10	5	36	9	14										23						124
G6	43						43	26	20						4			14				39	189
G7	21	13					17	8											20	10		13	102
bj	64	40	10	26	36	28	114	34	20	24	16	25	15	20	54	64	98	14	32	10	54	68	

Table (3) The optimal allocation of buses to various routes with the objective of minimizing fuel consumption

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	ai
G1													15	20								13	48
G2															54			1	31			40	126
G3												25				64	98		1				188
G4		40																		10	29		79
G5			10	26	36		12														25	15	124
G6	64					28		34	20	24	16							13					189
G7							102																102
bj	64	40	10	26	36	28	114	34	20	24	16	25	15	20	54	64	98	14	32	10	54	68	

CONCLUSION

In conclusion, this study addresses a solution to the Transportation Problem using a combination of mathematical modeling techniques and heuristic search algorithms, specifically applied to the context of the Cairo Transport Authority transportation network. The results of the study demonstrate that significant reductions in fuel consumption and carbon dioxide emissions can be achieved without compromising service quality or customer satisfaction.

Through the optimal allocation of buses to different routes, the company can reduce non-productive kilometers and fuel waste, resulting in a reduction of over 400,000 kg of carbon dioxide emissions annually. These findings have important implications for transportation planning and management, highlighting the potential benefits of adopting sustainable transportation solutions to mitigate the negative environmental impacts of transportation.

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