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Analysis of Carbon Footprint and Comfort for Bus System Regarding Optimum Daily Trips

Yetis Sazi Murat*, Muhammed Demirkollu & Selim Saldiroglu
Pamukkale University, Faculty of Engineering, Dept. of Civil Engineering, 20070, Denizli, Turkey

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Sustainable and smart management of public transportation systems depends on continuous monitoring and analysis of the data collected at regular intervals. One of the key research topics in this area is determining bus service frequency and developing appropriate schedules. The number of buses and their frequencies have a significant impact on the entire transportation system, affecting all users of the network. To address this issue, bus service frequencies during peak hours should be determined based on passenger demand. In this study, the daily frequencies of the bus system of a city (Denizli, Turkey) were investigated, the carbon footprints of the system were analyzed, and suggestions were provided. This is determined by the model developed regarding the linear optimization method. The goal programming approach is used in the analysis. The existing frequencies are compared with that provided by the goal programming approach. Additionally, the results obtained are investigated by a cost analysis regarding different benefit rates (carbon footprint, total kilometer, and passenger comfort) for the public. By implementing the recommended bus service frequencies, significant financial and environmental improvements can be achieved.

Keywords: Bus system, Carbon footprint, Linear goal programming, Passenger comfort, Public transportation

Introduction

One of the primary causes of climate change is the inefficient use of resources, leading to an increase in carbon emissions. Approximately one-third of harmful gases originate from transportation systems.[1] Research and improvements in transportation systems can have a significant impact on addressing climate change. Therefore, it is necessary to support public transportation systems by reducing the reliance on individual vehicles and enhancing the service quality of the system. A reliable public transportation system, properly integrated with other modes of transportation, will be preferred by users, and contribute to the sustainability of urban life. Regularity of service frequency is a crucial feature of a reliable public transport system, which relies on constant system monitoring, scientific data analysis, interpretation of results, and system refinement.

Various methods are employed for determining bus frequencies, including analyzing data obtained from passenger counts, occupancy levels, and minimum frequency standards. When determining the appropriate service quality and optimal service frequency, it is essential to consider the budget allocated for gathering relevant passenger-load data. Numerous studies have been conducted on this subject, examining the number, frequency, and schedule of headways in public transportation systems.

Previous studies have explored optimal headway numbers, frequency determination at specific time intervals, and the corresponding schedules. Vuchic[1] developed equations based on the number of passengers and bus capacity within the peak hour to identify the optimal frequency for each line. This study is theoretically important in terms of proposing a relation for calculating the service frequency according to certain assumptions. Chakraborty presented solutions for optimizing bus routes and frequencies using a genetic algorithm, considering factors such as bus fleet, capacity, stopping times, and maximum/minimum frequencies.[2] Total waiting times and transfer times of passenger was considered in the study, optimum fleet size and schedule was determined, and the waiting times of the passengers were minimized with the proposed GA based approach. Ceder conducted a study on efficient data collection methods for determining bus trip frequencies and interval values, utilizing vehicle-based and point-based measurement techniques. The collected data played a significant role in proposing alternative schedules to achieve minimum bus frequencies.[3]

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*Author for Correspondence
E-mail: ysmurat@pau.edu.tr

Other studies focused on cost-effective and rational headway scheduling systems, taking into account factors such as service cost, fleet size, and passenger capacity.[4] The concept of multi-criteria decision-making was explored to determine optimal service frequency values considering passenger demand, fleet size, and trip duration using various goal programming models.[5] The optimum bus service frequencies were determined regarding 180 minutes of total travel time constraint with a goal programming model developed by Alp.[5] Additional studies investigated bus stop locations, bus trip frequencies, and models for optimizing bus service frequency and stop locations using fuzzy linear programming and linear goal programming approaches.[6,7] Uludag modeled bus systems of Izmir, Turkey, optimized the bus stop locations by fuzzy linear programming approach, and obtained 36% gains for total travel time.[6] Additionally, the bus service frequencies were decreased by about 26% with a linear goal programming model proposed by Murat *et al.*[7]

Further research considered the impacts of real-time information on user behaviors, such as shortest total travel time, shortest pre-trip time, shortest walking time, and shortest riding time, to determine optimal bus frequencies that minimize users' total travel costs.[8,9] Deri investigated bus service frequency and used linear goal programming, obtained 36% decrease in service frequency and 67% gains in reserve capacity of the system.[8] Optimization models were developed to analyze optimal headway and length for public transit systems, considering externalities and aiming to minimize total system costs.[10] Shyue and Trun obtained about a 32% decrease in bus service headways and a 26% gain in total system cost with the optimization model.[10] The use of alternative energy sources to reduce emissions was also explored, demonstrating the potential to reduce the carbon footprint of transit operations while slightly increasing operating costs.[11] In the study by Li and Head, the NO_x and PM emissions are reduced by about 30–35%, however, it is obtained about 15% in CO_2 emission with a 10% increase in total operation cost.[11]

Studies have shown the benefits of using real-time operational tactics in reducing environmental impacts, with a focus on minimizing total passenger travel time and maximizing direct transfers.[12] Nesheli *et al.* obtained 5% reduction in inorganic emission to air by the proposed model.[12] The optimization models about service planning were developed to improve reliability and operator profit, leading to improved service quality and reduced headway coefficient of variation at stops.[13]

These studies enhance the understanding of optimal frequency determination and provide valuable insights for improving public transportation systems. By employing appropriate methodologies, analyzing relevant data, and considering several factors, public transport operations can be made more efficient, reliable, and environmentally sustainable.

In this study, the effects of the reorganization of bus lines on passenger comfort and carbon emissions were investigated. In previous studies, these issues were not considered properly, and the effect of the rearrangement of bus frequencies and stop intervals on the financial gain or system performance was examined. In addition, in previous studies, analyzes were performed based on 3-hour data, and in this study, daily data were examined. The main difference of this study from previous studies is that it deals with the travel comfort parameter, which is effective in users' preference for the bus system, and the concepts of carbon footprint, which have not been considered much before. It is possible to determine only the optimum frequency of trips in a way that will meet the daily capacity constraint, but in this case, as the number of trips decreases, the physical space allocated to the passengers will also decrease, thus the comfort of the travel will decrease. To draw attention to this issue, this study was carried out and the necessity of considering the comfort of travel was emphasized. The second important difference of the study is that, in terms of sustainability in transportation, the optimum number of trips in the proposed model is considered in terms of the carbon footprint of the bus system. In previous studies, it was seen that this issue was not addressed between the developed models and the results obtained. In previous studies, it was focused on the gains to be achieved in terms of monetary costs by rearranging the trip frequencies, but the concepts of travel comfort and carbon footprint were not examined. In this sense, the difference of the conducted study from previous studies has been revealed.

The main objective of the study is to analyze daily service frequencies in public transportation systems, propose a model for determining the ideal frequency, and investigate environmental effects (carbon footprints) and passenger comfort. The study aims to determine the optimal daily bus public transportation frequencies and identify steps necessary for the sustainability of public transportation systems by analyzing data using the linear goal programming model. Within the scope of the study, when the problem of reorganization of bus service frequencies is examined in detail, it is seen that the buses serving on predetermined lines operate in a certain time interval. Therefore, since the routes are fixed (predetermined) and the service time interval is within certain limits, it has been understood that the problem has a linear structure mathematically, and it has been concluded that it can be rearranged with linear programming approaches to meet the travel demands at the stops, depending on time and capacity constraints. In this context, the use of a linear goal programming approach was preferred. The data from Denizli Metropolitan Municipality Transportation Inc. are included in the study to enhance system efficiency by re-evaluating current daily frequencies based on this data.[14]

The conceptual framework of the analysis used in this study is shown in a flowchart as Fig. 1.

Materials and Methods

This study focuses on the bus system of Denizli, a city with a population of approximately 1 million. The bus systems are managed by a company associated with the Metropolitan Municipality. The travel demands in the city center are met by a fleet of 230 buses dedicated to public transportation. The study utilizes data from a total of 50 bus lines to analyze passenger demand. Daily, monthly, and yearly capacities were calculated based on this data.

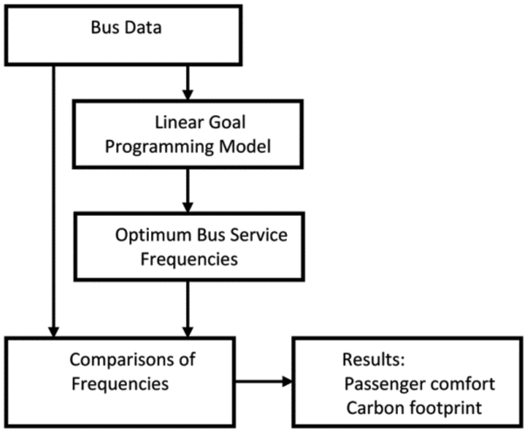

Fig. 1 — Conceptual framework of the analysis

The bus system operates a total of 3,074 daily bus trips, including 1,521 one-way trips and 1,533 round trips, covering 50 routes with a fleet of 230 vehicles. In 2019, the company provided transportation to a total of 31,099,144 passengers on weekdays, utilizing 209 vehicles. The total distance covered in 2019 amounted to 14,625,747 kilometers, averaging approximately 40,070 kilometers per day. The average operational speed of the system, considering the completion times and distance covered per trip, was determined to be 17.65 km/h.

In the bus system, there are 1,594 bus stops on departure routes and 1,623 stops on return trips. These bus stops are located in close proximity to each other, following international standards. The close distance between stops significantly impacts both travel time and cost.

Analysis of the Bus System Data

The data for the bus system in this study was obtained from the Metropolitan Municipality of Denizli city. The numbers of buses for each line, existing service frequencies, fleet size, bus type and capacity of each bus are considered in the analysis. The 50 bus lines examined within the scope of the study serve with approximately 3074 daily trips. In the research, data in different months throughout the year for 2019 were examined, and sample data from March and August were studied. Due to the differentiation of daily trips on weekends and weekdays, three-day data were considered in the sample, two days during the week and one day at the weekend. Therefore, the busiest days for weekdays and weekends were examined. In this sense, the results to be obtained may change due to the change of data for different seasons and days. Therefore, the findings obtained in the study represent only the seasons and days considered.

Due to the impact of the COVID-19 pandemic on public transportation usage, the data utilized in this study pertains to the year 2019, specifically obtained from the Smart Fare Collection and Management System Data of Denizli Public Transportation (unpublished data).

In 2019, the total number of individuals who chose buses as their mode of public transportation amounted to 31,099,144 people. The month with the highest passenger volume in 2019 was March, during which 2,968,489 people were transported (Fig. 2). In terms of average capacity, the proportion of passengers transported in March relative to the total passenger

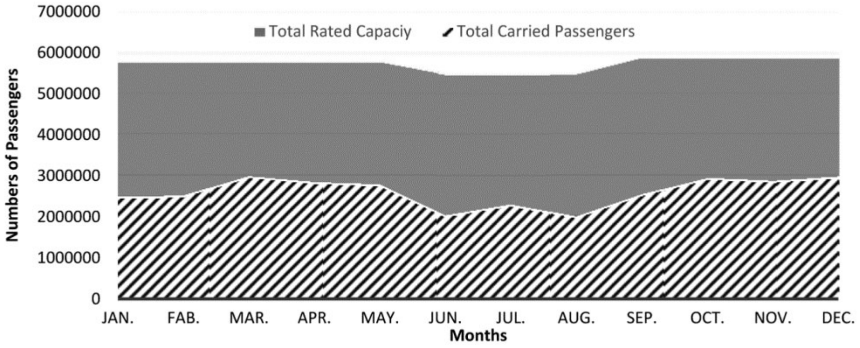

Fig. 2 — Monthly passenger boarding chart for 2019

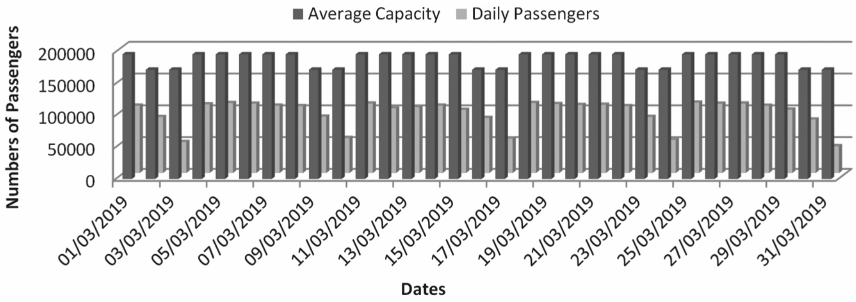

Fig. 3 — The chart for passengers transported in March 2019

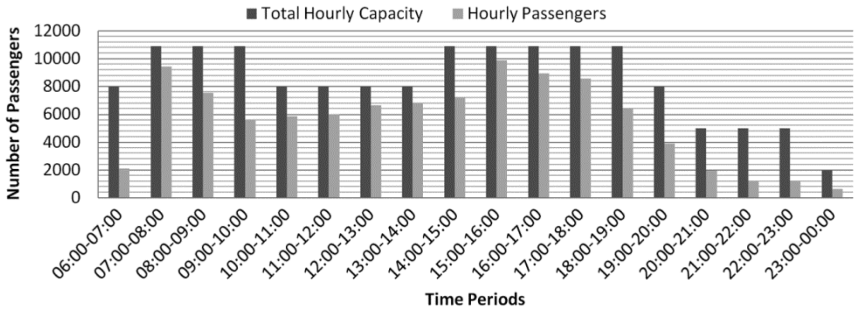

Fig. 4 — Hourly chart of the day with the most passengers transported in 2019

capacity was 0.502. The distribution of daily passenger demand and capacity values for March 2019 is shown in Fig. 3. The peak number of passengers transported throughout the year was observed on March 25, 2019 (Fig. 3). The average hourly capacity, based on calculations, was estimated at 10,900 individuals. The total number of passengers transported in a day was recorded as 110,821 people, equating to a ratio of 0.57 in relation to the total capacity.

The number of bus trips and capacity varies between the winter and summer seasons. Considering this information, the average annual capacity and passenger ratio is determined to be 0.45. Additionally, notable decreases in the number of passengers may occur during periods when schools are on holiday.

As depicted in Fig. 4, the demand for public transport reaches its peak during rush hours, representing the time interval with the most efficient capacity utilization. However, this level of demand cannot be sustained throughout the day, as demand is consistently lower than the capacity of the bus fleet across all time periods. To enhance the efficiency of the system, an optimization model is developed in this study to determine the optimal frequencies of the bus systems based on daily passenger demand figures.

The Daily Bus Service Frequency Model (DFMOD)

In this study, the Daily Bus Service Frequency Model (DFMOD) was developed using the linear goal programming approach. The model aimed to determine the optimal number of headways for the bus system. Decision variables, system constraints, and the objective function were defined to create the model, which was solved using the WinQSB software.[15]

The analysis focused on the busiest days in 2019, considering the passenger transport of 50 bus lines operated by the Denizli Metropolitan Municipality. The number of passengers and the number of bus trips were analyzed to determine the frequency and quantity of trips on days with high passenger demand. The goal was to optimize the number of trips and maximize profits by identifying additional trips and considering their benefits.

The model incorporated parameters such as passenger capacities, travel times, and trip lengths as basic variables. The decision variables belonged to the 50 bus lines, and the busiest days in the winter season (March 25, 2019), summer season (August 8, 2019), and all Sundays (March 10, 2019) were considered.

The details of the model are explained in the following.

Step 1: Decision Variables

The determination of optimum bus service frequency is affected many variables such as the number of buses operating on a route, the frequency of bus departures, fleet size, passenger demand etc. The frequency of each line is considered as the decision variables in the DFMOD model.

Step 2: Goals

For the effective management of bus systems, the expectations of users and operators should be considered. The expectation of the users is to provide more comfortable, economical, and fast transportation. However, the operator wants to offer a more economical and efficient public transportation service. In this sense, it is important to use the existing fleet efficiently. With the developed model, goals were selected to meet these expectations and it was aimed to ensure the most effective use of the existing system infrastructure. The goals of the model can be listed as the following.

1. Minimizing passenger waiting times.
2. Minimizing operational costs (fuel, driver wages, maintenance, etc.).
3. Maximizing the capacity of the system.
4. Maintaining a consistent level of service to ensure passenger satisfaction.

In goal programming, the goals are defined with constraints. For the DFMOD model, three goals are considered time, capacity, and distance namely.

For time goal constraints, the number of buses in the fleet for a given day was compared to the time required for one frequency of each line, as well as the total distance covered in both directions (departure and return) and the overall distance covered by each line. Previous studies have often examined frequency based on peak hours of the day. The number of frequencies was observed to decrease in response to passenger demand, and the impact of this change on costs was analyzed. However, previous studies on bus trip frequency have typically focused on specific time periods, such as the 180-minute morning peak hours.[14]

The equation used for the time goal constraint is as follows:

$$\sum_{i=1}^{50} t_i X_i + d_1^+ + d_1^- = T \times B \qquad \dots (1)$$

where, t_i is travel time of each bus line, B is the number of available buses, X_i is the number of frequency for the line i, T is the time interval (1 day), d_t are the deviation variables; (+) represents positive and (-) represents negative values respectively.

The equation used for the capacity goal constraint is as follows:

$$\sum_{i=1}^{50} C_i X_i + d_2^+ + d_2^- = \sum_{i=1}^{42} K_i \qquad \dots (2)$$

where, C_i is the capacity value of the bus type used in each line, K_i is the passenger demand value in each line, X_i is the number of frequency for line i, d_t are the deviation variables; (+) represents positive and (-) represents negative values respectively.

The equation used for distance goal constraint is as follows;

$$\sum_{i=1}^{50} m_i X_i + d_3^+ + d_3^- = M_T \qquad \dots (3)$$

where, m_i is the distance covered by each line, M_T is the distance covered daily by the system, X_i is the number of bus service frequency for the line i, d_t are the deviation variables; (+) represent positive and (–) represent negative values respectively.

Step 3: Deviation Variables

Deviation variables are defined for time, capacity, and distance goal constraints. The goal programming model used only negative deviation variables (d_t^-) for the success functions because positive deviation variables (d_t^+) would indicate a surplus in the constraints related to the subject. Specifically, (d_1^+) represents the surplus time for the time target constraint, (d_2^+) represents the surplus capacity for the capacity target constraint, and (d_3^+) represents the surplus distance for the distance target constraint. On the other hand, the negative deviation variables (d_1^-) in the success functions indicate the potential time savings, (d_2^-) represents the additional number of passengers that can be carried, and (d_3^-) represents the extra distance that can be covered.

Step 4: The Objective Function

In linear goal programming the objective function represents the total deviations from the desired goals. This function should be a combination of the deviation variables. The objective is to minimize the sum of these deviations. When creating the objective function in the model, equal priority was given to the time, capacity, and distance target constraints.

The objective function created is shown below as a minimization of the sum of the negative deviation that belongs to these three constraints.

$$min\ S = d_1^- + d_2^- + d_3^- \quad \ldots (4)$$

Step 5: Constraints

For the DFMOD model, the goal constraints and system constraints are defined. The goal constraints are defined on the right sides of the equations (Eqs 1–3) given above. The number of available buses and time interval (18 hours of a day) is defined as the constraints for the time goal in Eq. 1, the passenger demand value is defined as the constraint for the capacity goal (Eq. 2), and the daily covered distance by the system is considered as the constraint for the distance goal defined in Eq. 3.

In addition to these, system constraints were defined based on bus travel times, route lengths, and bus capacities to meet passenger demand for each line. The system constraints here can be expressed by the following equation:

$$S_i x C_i = K_i \quad \ldots (5)$$

where, S_i is the bus service frequency values for the lines, C_i is the capacity values of the bus type used in each line and K_i is the passenger demand values in each line.

The DFMOD model is executed using the constraints and objective function described above and the Windows-based WinQSB software.[15]

Results of the Daily Bus Service Frequency Model (DFMOD)

The Daily Frequency Model (DFMOD) is a linear goal programming model that was created to determine the optimal number of bus service frequencies to be made in a day. The model considers the entire system by analyzing the lines in both directions. By comparing the data obtained from the general examination of the system with the data from the departure and return directions, the optimal number of frequencies is determined.

The frequencies obtained from the DFMOD Model were compared with the current ones based on factors such as bus fleet size, bus capacities, line travel times, and passenger demands. Fig. 5 provides sample comparisons of the frequencies on March 25, 2019, which was the day with the highest number of transported passengers.

As seen in the figure, the current frequencies on many bus routes exceed the necessary amount, resulting in economic and environmental losses. The suggested frequencies by the DFMOD model are deemed sufficient to meet passenger demand and prevent these losses. By considering 100% fully

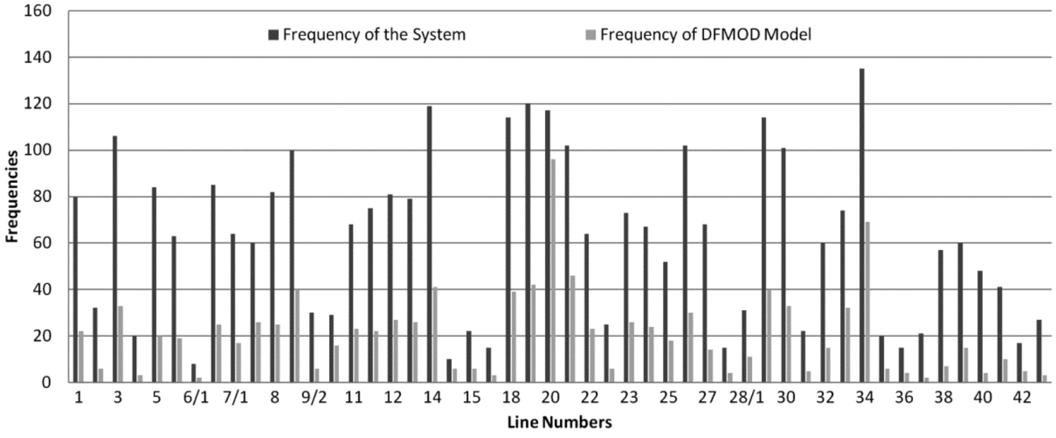

Fig. 5 — Graph for the current system and model frequencies on March 25, 2019

loaded transportation as a system and conducting cost-benefit calculations, the DFMOD frequencies, along with a 30% and 50% increase representing social benefits, have achieved maximum benefits.

However, even with the increase in social benefits, it is observed that the current frequencies still surpass the calculated values. Sample comparisons between the current ones and the DFMOD model frequencies are presented in Table 1.

The excessive trips caused by the irregularity of frequencies in the current system contribute to increased fuel consumption and negative environmental effects, such as emissions and carbon footprints. Implementing the calculated ideal trip frequencies would help mitigate or significantly reduce these adverse effects.

As shown in Table 1, the goal programming approach, which determines optimal service intervals, reveals significant improvements in the number of daily trips. By reducing the number of daily trips on bus lines, the distance traveled without passengers (empty trips) will also decrease. Consequently, there will be a decrease in emitted emissions, leading to notable enhancements in terms of carbon emissions. Previous studies examining the carbon footprint of bus systems have indicated varying values depending on the length of the trips, ranging from 80 to 110 grams per kilometer traveled.[16–19]

Table 1 — Sample comparisons of current frequency values with the DFMOD (25.03.2019)

Bus Line No	Number of Headways (System)	Number of Headways (DFMOD MODEL + 30%)	Number of Headways (DFMOD MODEL + 50%)
1	80	29	33
2	32	8	9
3	106	43	50
4	20	4	5
5	84	26	30
6	63	25	29
7	85	33	38
8	82	33	38
9	100	52	60
10	29	21	24
30	101	43	50
31	22	7	8
32	60	20	23
33	74	42	48
34	135	90	104
35	20	8	9
36	15	5	6
37	21	3	3
38	57	9	11
39	60	20	23
40	48	5	6
41	41	13	15
42	17	7	8
43	27	4	5

In this study, the carbon footprints of the bus systems were calculated using an approximate unit value of 100 g/km. The carbon footprints were determined based on this unit value and the trip lengths of the bus lines. Sample comparisons of the daily trip lengths and carbon footprints of the bus lines are presented in Fig. 6.

The comparisons depicted in these figures demonstrate that the model results achieved an average reduction of 54% in daily trip lengths compared to the current situation, specifically for March 25, 2019, when passenger density was at its highest. Additionally, it was found that the carbon footprint values of all bus lines decreased by an average of 36 kilograms per day. Considering the weighted average based on the daily trip lengths of the lines, an average reduction of 51 kilograms was observed in the carbon footprint value.

By optimizing the service frequencies of the bus lines, fuel consumption, carbon footprint, and total travel length have been minimized. In addition to these parameters, the comfort parameter, which is important for passengers, was also taken into consideration.

Travel comfort is an important criterion for passengers in the use or preference of bus systems. Users can decide on the transportation mode selection according to the comfort parameter, after the cost of the trip. In this context, users desire to travel more comfortably, and accordingly, they plan their travel activities by evaluating their transportation options. For this reason, the concept of travel comfort, which is discussed within the scope of the study, is important in the evaluation of bus systems in terms of users. However, in bus systems, it is often not possible to increase the comfort of travel or bring it to ideal levels due to cost constraints. Increasing the number of buses in the fleet causes a significant cost and it is not possible to keep the travel comfort at ideal levels. In this case, improving the comfort of travel by using the bus fleet more effectively (by changing the frequency of services on some lines) is considered the most appropriate solution. Within the scope of the study, an example solution is presented according to this method.

The spatial capacity value offered by the buses on each line for standing passengers was calculated to assess passenger comfort. The total area size of the

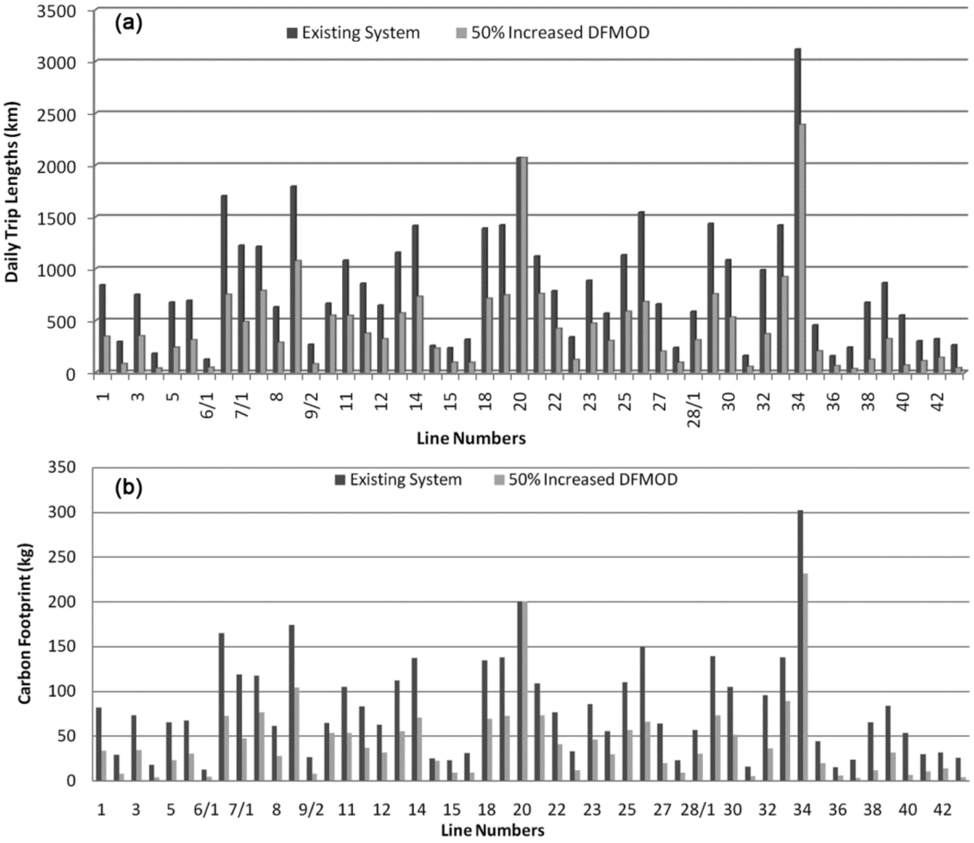

Fig. 6 — Daily trip length (a) and carbon footprint (b) comparisons of the lines for March 25, 2019

buses for both standing and seated passengers was considered, and the space allocated for standing passengers was determined based on TCRP standards.

Upon examining the buses in terms of standing passengers, it was found that 18-meter-long buses with a capacity of 150 passengers could accommodate 115 standing passengers, providing each passenger with 0.29 m² of area when fully loaded. Similarly, 12-meter-long buses with a capacity of 73 passengers could carry 100 standing passengers, providing each passenger with 0.27 m² of area when fully loaded. Furthermore, 9-meter-long buses with a capacity of 65 passengers could carry 40 standing passengers, allowing each passenger to have 0.30 m² of area when fully loaded. Therefore, when the system operates at full capacity, it can offer passenger comfort within a range of 0.25 m² to 0.30 m² per standing passenger.

These figures indicate the level of comfort or discomfort according to the TCRP definitions provided in Table 2.

A comparative representation of the daily comfort values for line 20, showing the existing system's data and the model's data as samples in Fig. 7.

As seen in the figure, the existing systems' irregularities in service frequencies lead to fluctuations in passenger comfort, whereas the DFMOD model provides more stability in this regard.

In this study, the impact of optimizing the service intervals for the bus system on passenger comfort was examined, and the weighted average passenger comfort was calculated based on the number of passengers carried throughout the system. The calculations revealed that while the average passenger comfort in the current system was 0.40 square meters per passenger, it decreased to an average of 0.35 square meters per passenger with the recommended 50% increased DFMOD model. Despite the decrease in passenger comfort, it is evident that significant improvements have been achieved in terms of carbon footprint, daily travel length, and monetary cost.

Regarding these benefits, an average daily gain of a 40% in travel distances, a 30% in costs, and a 40% in carbon footprint has been achieved. These gains correspond to an average annual cost reduction of 2.5 million dollars and an average

Table 2 — Standing passenger space and comfort conditions by TCRP[15]

Standing passenger space (m²/Passenger)	Passenger Comfort	Conditions of Enterprises
>1.00	1) Passengers can act as they wish. 2) The seating rate of passengers is high. Example: Rail systems	1) Inefficient service provision by the public transportation enterprise when peak loads are considered. 2) When the return is considered in comparison with the service in a certain direction, it may be less efficient.
0.50–1.0	1) Passenger transport load with high passenger comfort area	1) High-quality service is provided for the newly designed rail systems. 2) Easy movement within the vehicle is ensured.
0.40–0.49	1) Passengers can travel standing without having physical contact with each other. 2) The area covered by the seated and standing passengers is equal.	1) A balanced enterprise condition in terms of capacity and comfort. 2) Movement to the door starts to become difficult and waiting time increases.
0.30–0.39	1) Passengers sometimes come into contact with each other. 2) Standing passengers have less room than seated passengers.	1) Enough movement space is provided in the vehicle.
0.20–0.29	1) Proximity that irritates people. 2) Frequent body contact takes place and people cannot move along with their bags.	1) The highest carrying capacity used for calculations. 2) Movement between doors is quite difficult and waiting time at the bus stop increases. 3) Passengers wait for the other passengers in the vehicle to move towards the free spaces in the bus to get on.
<0.20	1) People travel in extremely cramped conditions.	1) It gets almost impossible to move in the vehicle. 2) People wait for the other passengers in the vehicle to find a free space and move towards to get on. 3) People wait for the next bus instead of getting on.

Note: Public vehicles are usually calculated for standing passengers to be 50% more than seated ones. This calculation is especially for light rail systems, metro, and monorail systems.

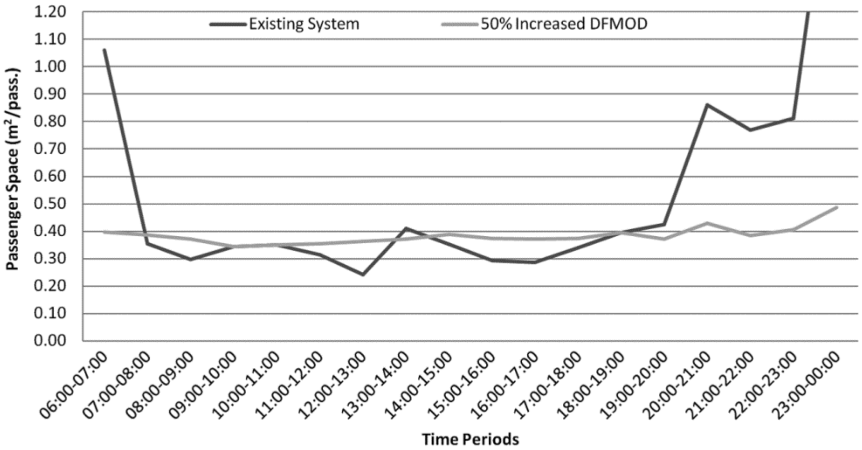

Fig. 7 — Sample comparison of the system and DFMOD model comfort values for Line 20

annual carbon footprint reduction of 1000 tons. Considering that these gains are calculated for Denizli, a medium-sized city in terms of population, it can be concluded that implementing the model in other similar cities and countries can make a significant contribution. Undertaking such studies is beneficial, particularly in terms of addressing climate change and its global impacts, as well as promoting sustainability.

Conclusions

In conclusion, this study focused on enhancing the efficiency of the urban bus system in Denizli, Turkey, while taking into account environmental impact and passenger comfort. Through the development of a linear goal programming model tailored to Denizli's data, several key findings emerged:

- The current bus system operates inefficiently, particularly during periods of low passenger density. Implementing a 49% reduced headway schedule on the busiest day analyzed can lead to more efficient operations.

- The optimized schedule yields substantial daily savings, including a 40% reduction in total trip lengths, a 30% cut in operating costs, and a 40% decrease in carbon footprint.
- While passenger comfort slightly decreases in some instances, it still meets TCRP guidelines, with 0.42 square meters per passenger compared to the current 0.84 square meters.

This optimized bus system offers significant benefits for sustainable transportation, especially regarding reduced carbon emissions. While the findings pertain to Denizli, the study's methodology can be applied to different cities globally, enhancing objectivity.

Future research should explore integrated models considering carbon footprint, passenger comfort, and cost simultaneously. Developing dynamic software with AI support for real-time analysis and bus service adjustment could further enhance system management. In essence, this study underscores the importance of efficiently operating urban bus systems, leading to more sustainable and effective transportation.

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