Considering Sustainability in the Planning of Transit Systems: Istanbul Case

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Abstract— **Traditionally, minimization of the total travel time spent by the passengers in the system is the most preferred objective while planning transit systems. To satisfy this objective, forecasted travel demands between zones and characteristics of the available fleet are taken into account, and at the end of the planning process, optimum frequencies of each transit lines are identified. Unfortunately, this planning approach is not sufficient as the negative effects of the global warming are growing each day. Fossil fuels are the primary energy sources for transport systems and accordingly, the emission of greenhouse gases especially carbon dioxide is accredited to this industry. Hence, it is impossible to ignore environmental requirements in the transit planning phase. In this study, we develop a bi-level and bi-objective optimization model to identify the optimum line frequencies. One of the objectives is to minimize the mean travel time of the passengers. The other objective is to minimize the total emission. A genetic algorithm is developed to solve this mathematical programming problem. A large instance related to Istanbul transit system involving 39 zones and 463 bus lines is solved with this solution method and results are elaborated.**

Keywords—**Sustainable transit system planning, greenhouse gases emission, bi-level programming, genetic algorithm.**

I. INTRODUCTION

Public transport is a shared passenger transportation service which is available for the use of large masses. Public transportation system is an important and essential part of big and crowded cities. Increasing car ownership in the societies causes many important economical, environmental and social problems. This problem can be solved by public transportation system so transportation system has become one of the most significant issues in the cities.

Due to the traffic congestion, passengers total travel times are increased. Time is a nonrenewable resource so travel and waiting times should be minimized by public transportation system. Another aspect related to the transportation is that it is a major source of pollution and greenhouse gases (GHS) especially carbon dioxide (CO_2). Greenhouse gas emissions of public transportation are increasing at a faster rate than any other energy using sector.

According to International association of public transport (UITP) survey, 23% percent of total CO_2 gases are composed by transportation; including rail, bus, sea, air transportation systems and 98 of all land transport depends on fossil fuels [1].

Governments produce new policies to provide sustainability of transportation systems. There are different solutions for sustainability transport. Advantages in technology renewable sources are used for transportation with costly investments such as using solar, wind or biofuel. The other way of providing sustainability transport is to optimize transit line frequencies regard with minimizing greenhouse gas emissions.

Transportation impacts on sustainability are investigated along three dimensions; economic, social and environmental. Economic criteria compose of traffic congestion, mobility barriers, crash damages, transportation facility costs, consumer transportation costs and depletion of non-renewable resources. Social criteria include inequity of accessibility, mobility disadvantaged people, human health impacts, community cohesion, community livability and aesthetics. Environmental criteria compose of air pollution, climate change, habitat loss, water pollution, hydrologic impacts and noise pollution. By considering all these dimensions concurrently, it is possible to create a sustainable transportation system which is indispensable to improve the life quality in cities. To provide sustainability transportation depends on transportation decision making, automobile dependency, transportation equity, facility design and operations, land use, developing regions decisions [2].

Sustainable transport implies finding a proper balance between (current and future) environmental, social and economic qualities [3]. Environmental, social and economic qualities have different effect on the passengers. Their content can vary with passenger perspective. Sustainable transportation should provide these qualities. For the environmental side different transport modes are responsible for approximately 30% of global warming. This ratio is much larger compared to those of energy production or industry. In Europe, even despite increasingly cleaner engines, CO_2 emissions have not decreased, but keep growing (+ 25 % since 1990) [4].

Global warming has become one of the critical issues all over the world. Governments and organizations focus on this topic. Public transportation companies from different countries start to put new objectives for providing sustainability transport. Some of them determine deadline of sustainability transportation projects and they have an arrangement with environmental organizations such as UITP. For example Translink, British Columbia, Canada began to collect bus idling data over one year using a newly

implemented Vehicle Data Capture System. The data showed that bus idling represented up to a peak of 21% of operating time of the buses, fuel consumption costs approximately CAN$ 1,500,000 burning 1.76 million liters of fuel and causing 440,000 hours of unnecessary engine wear. Policies to manage this better (taking into account seasonal needs) not only reduced fuel consumption but also brought environmental benefits and reduced CO_2 emissions [5].

The paper is organized is as follows: we present a brief literature of previous work done related with our model in the first section. Then, a bi-level line frequencies optimization model that has the objective to reduce average traveler transit time and CO_2 emissions is presented. As the proposed model is bi-level, a special solution algorithm is developed and its details are given in section four. To show the usefulness and efficiency of our approach, a case study of Istanbul bus network is investigated and the results are elaborated. The final section contains some concluding remarks and future research directions.

II. LITERATURE SURVEY

In the literature there are lots of different studies about public transportation systems. Many of them are related to transit assignment, optimizing transit line frequencies, time dependent assignment, game theory model, stochastic dynamic assignment models, user equilibrium (UE), stochastic user equilibrium models (SUE).

Transit assignment models concerns the selection of routes (paths) between origins and destinations in transportation network. These model objectives are minimizing the total expected travel and waiting time [6, 7,8] perceived total travel times [9], expected travel cost [10,11], general cost [12] (including; in-vehicle time, waiting time, walking time, a line change penalty), total vehicle operation cost [13], optimize transit lines timetables with fleet size and vehicle services [14], utility maximization [15]. Transit assignment models are solved with the gradient projection method, minimum cost hyper-path search algorithm, method of successive averages algorithm, iterated local search algorithm and Newton method.

Transit assignment models with uncertainty turns into stochastic transit assignment models. Objectives of stochastic transit assignment model can be minimizing generalized cost; in-vehicle time; waiting time; walking time; and a time penalty for each line change with timetable and route choice variables. This model is solved branch and bound algorithm and its application is The Hong Kong Mass Transit Railway [16]. Minimizing perceived cost stochastic transit assignment model with route choice, day to-day variability, OD demand with varying different times, frequency variables is solved method of successive averages algorithm [17].

Transit assignment models with varying times turns into dynamic transit assignment models. Objectives of the model are minimizing number of vehicles at a time interval or perceived cost, the expected disutility, the average expected travel time. These models are solved method of successive averages, simultaneous perturbation stochastic approximation method [18, 19, 20, 21].

Stochastic user equilibrium (SUE) transit assignment model is that routes get fuller and thus slower when more travelers select them. The solution is, thus, not a simple "best path on empty network" calculation. The model objective is minimizing the expected total travel time with passenger overload delay and frequency variables. This model is solved by algorithm has been proposed by Bell for solving a SUE road traffic assignment problem with queues with explicit capacity constraints [22]. Stochastic user equilibrium (SUE) transit assignment model with scheduled time-tables are used to describe the movement of vehicles turns into stochastic dynamic user equilibrium (SDUE) assignment problem. These model objectives are minimizing expected perceived travel cost, the generalized travel cost. Stochastic dynamic user equilibrium (SDUE) assignment problems are solved with DYNASTOCH algorithm [23] and heuristic solution algorithm [24].

Probit based model objective is minimizing perceived time (in vehicle time + waiting time) with frequency and route choice variables. The model is solved by an operational solution algorithm in which the road users' 'perceived travel resistances' are simulated. Application of the model is Copenhagen's public transport network [25].

Two components of transit network design and scheduling model are basic line configuration problem and passenger line assignment. Objective of the model is minimizing total passenger in-vehicle travel time and total number of passenger transfers with route choice and frequency variables. The model is solved standard branch and bound algorithm. Application of the model is Hong Kong mass transit railway network [26].

The bi-level programming problem is a special case of multilevel programming problems with a two level structure. The problem can be expressed as follows: the transport planner wishes to determine an optimal policy as a function of his or control variables (y) and the users response to these controls, where users response generally takes the form of a network flow (x). The transport planner then seeks to minimize/maximize a function of both y and x, where some constraints may be imposed upon y as well as the fact that x should be a user equilibrium flow, parameterized by the control vector y. There exist many problems in transportation that can be formulated as a bi-level programming problem. Bi-level programming models for the transportation systems are transit frequency, market equilibrium, measurement of gas emissions throughout a traffic network, transit frequency design models. Upper level objective functions can be related to toll revenue, investments, time, accessibility, and so on. The lower level objective functions can be minimizing the travel costs, minimizing travel time. These types of models are solved with TAPAS algorithm, gradient projection method and special improved algorithms. [27, 28, 29, 30]

In this paper, we propose bi-objective bi-level optimization model to determine transit line frequencies. The two objectives considered at the upper level of our model are minimization of mean passenger travel time and total CO_2 emission. At the lower level, we aim to reduce the total passenger travel times given passenger demand and existing lines. The overall model is solved by an adapted genetic algorithm. With these unique features, our work fill an important gap in the literature.

III. TRANSIT ASSIGNMENT MODEL

Let us denote $G(\mathcal{N}, \mathcal{A})$ the directed graph with $\mathcal{N}$ as the set of nodes and A is the set of links. Let also $\mathcal{S}$ denotes the set of destination nodes, $\mathcal{A}_i^+$ and $\mathcal{A}_i^-$ the forward and backward star of node i respectively, and $\mathcal{L}$ the set of transit lines.

A. Upper Level Problem

When transit lines frequencies are optimized, the aim of transportation planning authority is to minimize the total travel time spent by the travelers in the network under the fleet size and line constraints. This traditional objective is also considered in our study. The other objective is to minimize the total CO2 emission due to the operating vehicles. When transit line frequencies are increased, the total travel time decreases. Meanwhile, increasing bus frequencies also leads to an increase in the total emission. In other words, these two objectives are in conflict. When our bi-objective model in (1)-(4) is solved, a set of Pareto optimum or non-dominated solutions are generated. Then, the planning authority has the opportunity to choose the time-emission pair that best suits its purpose.

$$\text{minimize} \quad \frac{1}{D} \sum_{s \in \mathcal{S}} \left(\sum_{a \in \mathcal{A}} t_a v_a^s + \sum_{i \in N} w_i^s \right) \qquad (1)$$

$$\text{minimize} \quad \sum_{l \in \mathcal{L}} e_l f_l \qquad (2)$$

$$\text{s.t.} \quad \sum_{l \in \mathcal{L}} t_l f_l \leq M \qquad (3)$$

$$f_l \geq \underline{f}_l \qquad\qquad l \in \mathcal{L} \qquad (4)$$

Here, D denotes the total travel demand between zones, t_a the fixed travel time on link a, v_a^s the flow on link a with destination s, w_i^s the total waiting time for passengers on node i with destination s, e_l the total CO2 emission for a vehicle operating on line l, and t_l the fixed in-vehicle travel time of line l, M the fleet size, and $\underline{f}_l$ the required minimum frequency for line l. The variable of this model is f_l which denotes the vehicle frequency for line l. In (1), we aim to minimize mean passenger travel time, while in (2) we aim to minimize the total network emission. Constraint (3) limits the total number of vehicles to be operated and constraint (4) lower bounds the frequency of a line.

B. Lower Level Problem

$$\text{minimize} \quad \sum_{s \in \mathcal{S}} \left(\sum_{a \in \mathcal{A}} t_a v_a^s + \sum_{i \in N} w_i^s \right) \qquad (5)$$

$$\text{s.t.} \quad \sum_{a \in \mathcal{A}_i^+} v_a^s - \sum_{a \in \mathcal{A}_i^-} v_a^s = g_i^s \qquad (6)$$

$$v_a^s \leq \left(\sum_{l \in \mathcal{L}} \delta_{al} f_l \right) w_i^s \quad a \in \mathcal{A}_i^+, i \in \mathcal{N}, s \in \mathcal{S} \quad (7)$$

$$v_a^s \geq 0 \qquad\qquad a \in \mathcal{A}, s \in \mathcal{S} \qquad (8)$$

Here g_i^s is the passenger demand at node i willing to reach destination s. The objective in (5) is to reduce the total passenger travel times. Constraint in (6) is the general flow balance constraint for network flows: the number of passengers leaving node i must be equal to the sum of the passenger incoming to and waiting at node i. Assuming that the passengers waiting at a node could take the first vehicle, constraint (7) relates links flows and nodes waiting times. Finally constraint (8) is for non-negative flows.

IV. SOLUTION METHOD

A. Solving Lower Level Problem

The proposed model in (5)-(8) is a large linear programming model. As the optimum solution of the lower level model will be needed several times when the upper level model will be solved iteratively, the lower level model should be solved efficiently. The first thing that can be remarked about the model in (5)-(8) is that it can be decomposed based on the destination. Hence, the overall problem can be solved optimally if each of the destination decomposed subproblem is solved optimally. If the special structure of the destination based decomposition is investigated, its similarity to the shortest-path problem can be recognized. In fact, shortest-path problem is a special case of our destination based decomposition ($f_l \to \infty$ and $w_i \to 0$). The algorithm provided below efficiently solves the subproblem related to destination node q [31].

Transit Route Choice Algorithm:
1. $u_i = \infty$ for all $i \in \mathcal{N}/\{q\}$, $u_q = 0$, $\bar{f}_i = 0$ for all $i \in \mathcal{N}$, $\mathcal{B} = \mathcal{A}$, $\bar{\mathcal{A}} = \emptyset$.
2. If $\mathcal{B} = \emptyset$ then go step 3
   Otherwise
       Find $a = (i,j)$ such that $u_j + t_a$ is the smallest value of $\mathcal{B}$
       $\mathcal{B} = \mathcal{B}/\{a\}$
       If $u_i \geq u_j + t_a$ then
           $u_i = \left(\bar{f}_i u_i + f_a(u_j + t_a) \right) / (\bar{f}_i + f_a)$
           $\bar{f}_i = \bar{f}_i + f_a$
           $\bar{\mathcal{A}} = \bar{\mathcal{A}} \cup \{a\}$
       Go back step 2
3. $V_i = g_i^q$ for all $i \in \mathcal{N}$
4. For every link $a \in \bar{\mathcal{A}}$ in decreasing order of $(u_j + t_a)$ do
       $v_a^q = \left(f_a/\bar{f}_i \right) V_i$
       $V_j = V_j + v_a^q$
       For all others arcs $a \in \mathcal{A}/\bar{\mathcal{A}}$ set $v_a^q = 0$.
5. $w_i^q = V_i/\bar{f}_i$ for all $i \in \mathcal{N}$

B. Solving Overall Problem

We make use of the Non-Dominated Sorting Genetic Algorithm (NSGA-II) [32] to solve the bi-level and bi-objective model given in (1)-(8). Within the general framework of genetic algorithm, every individual is represented with a vector of size $|\mathcal{L}|$ of real numbers. In other words, our objective is to identify what must be the frequency for each transit line. The steps of our adapted algorithm are given below:

1. Create the initial population by randomly selecting line frequencies that satisfy constraints (3) and (4) for each individual that made the population.

2. Find objective function values for the existing population. For each individual, first calculate the objective in (2). Then given line frequencies, use the transit route choice algorithm to find optimum line flows and waiting times. With this solution, the objective in (1) can be calculated.

3. Based on the objective functions values, calculate the non-dominance ranking and crowding distance of each individual.

4. To form the new population, first conduct a tournament among individuals to form the mating pool. The tournament is played by two or more individuals that are selected from the existing population and the one that has the lowest non-dominance ranking is added to the mating pool. If there are two or more players that have the lowest ranking score, the one with the largest crowding distance is added to the pool. İf there is a tie, the individual to be added to the pool is selected at random. The tournament process continues until the mating pool is filled.

5. Form the new population with the crossover and mutation of the individuals at the mating pool. Two parents are selected from the mating pool, and two children are created with their crossover. Then mutation occurs with a given probability. While parents return to the mating pool, the children are added to the new population. This process continues until the new population reaches to a determined size. Here it is ensured that constraints (3) and (4) are satisfied while genetic operators are applied.

6. If the maximum number of iterations is not reached, then go to step 2. Otherwise, identify non-dominated solutions from the existing population and display as a result.

V. CASE STUDY: ISTANBUL BUS NETWORK

To demonstrate the efficiency of our approach, we applied it to İstanbul bus network. İstanbul bus network is very large with 39 zones connected through 590 bus lines. As some lines are used very infrequently, we only investigated 463 of them. The total number of trips is 26,000 during all day. Although there are private companies operating buses in İstanbul, the central bus and bus rapid transit (BRT) network planning and management authority is Istanbul Electricity, Tramway and Tunnel (IETT). The total fleet size is around 5000 vehicles (IETT + privately owned). The fleet is composed of very different vehicles. However, we did not take this fact into account directly to keep our model simple. Instead, we assumed that the network is served with an average vehicle. The CO_2 emission of this average vehicle is set to 0.850 kg/km (Federal Test Procedure normalized) [33].

In this study, the morning peak (07:00AM-09:00AM) transit demand estimates for year 2011 are considered. Around 30% of the total transit demand is served bus lines. The estimated daily number of passengers for bus system is 3.5 million and around 30% of this demand is served during peak morning hours. The data are obtained from the Department of Transportation Planning of İstanbul Metropolitan Municipality.

NSGA-II is run for a population size 100, tournament size 2, crossover rate 0.80, Pareto front population fraction 0.20. As it can be observed from Figure 1, the population average of objective function values start to stabilize around 120 iterations. Hence the maximum number of iterations for the NSGA-II is set to 120. For the crossover operator, we
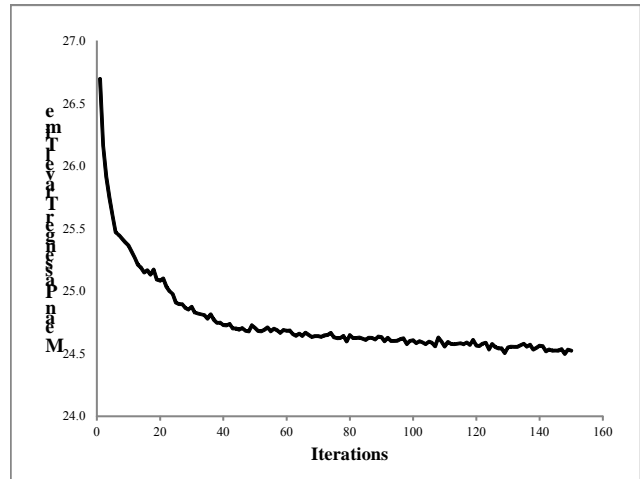

Fig 1. Plot of the population average of mean user time objective during the iterations of NSGA-II

first create a random binary vector. We then select the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the second parent, and combines the genes to form the child. For the mutation operator, a small number of solution vector elements are selected at random and the values of these elements are randomly increased or decreased. Both operators are arranged such that the produced children are always feasible. As we do not want to discontinue any existing line, the lower bound on the minimum frequency of each line is set to one.

Final results for 5 different runs of the NSGA-II are pooled and the final Pareto front is obtained after removing dominated solutions from this pool. These solutions are shown in Figure 2. The current frequency assignment is also shown in that figure. This solution is dominated by the Pareto optimum solutions of our algorithm. While it is possible to reduce mean passenger travel time for the same CO_2 level around 15%, it is interesting to observe that there is a room to cut more than a half of the total CO_2 emission for the same mean travel time level. This result is not difficult to explain because most of this type of transit networks are designed to minimize the total or mean passenger travel time. Moreover, many lines of the network are not operated harshly on the efficiency principle. Instead, many lines are continued despite low ridership or long travel distances.

The Pareto optimal solutions are provided but which one of them is sustainable is not fully answered. Surely solutions
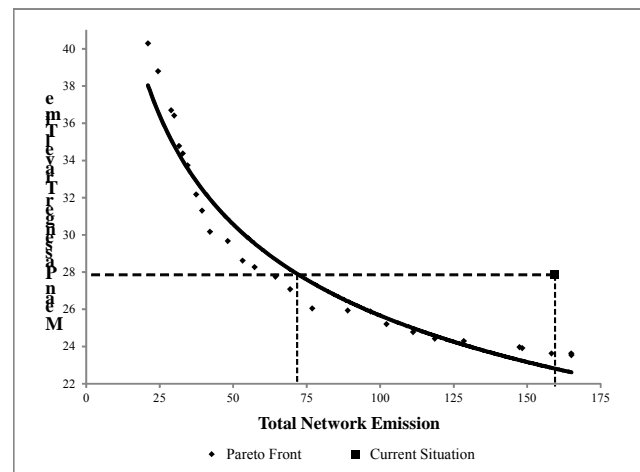

Fig 2. Pareto optimal solutions depicted in the objective functions space

lying on the two extreme of the trend curve in Figure 2 are not sustainable: they ignore the passengers in favor of environment or vice versa. We can ignore them. However, identifying the sustainable solution is not simple. In our case, if we had a specific figure of what is the sustainable in terms of per capita CO_2 emission and per capita transport time, we could then detect easily which of the Pareto optimal solutions is sustainable or how much these solutions are far from the sustainable solution. As these numbers are non-existing (in fact there is no a common understanding on these numbers), we should make an assumption and accept the solution that is "good enough" in both objectives as the most appropriate. Here we adopt the following convention: the solution that is "good enough" in both objectives is the one with minimal distance to the origin at the objective functions space. As the origin in this space corresponds to the ideal solution (yet impossible to attain), the closest Pareto optimal solution to the ideal solution can be considered as satisfactory. The distance is measured with Euclidean norm and paying equal importance (equal weights) to both upper level objectives. In our case, the solution which results in 28.61 minutes for the mean passenger travel time and 53.24 tones of CO_2 emission is a good solution. Compared to the current situation, the adaptation of this solution may lead to a slight increase (3%) in mean travel time but also to a significant emission reduction (66%).

VI. Conclusion and Future Research

While frequencies of transit systems lines are planned, minimization of the total travel time spent by the passengers is the most preferred objective. Unfortunately, this planning approach is not sufficient today. Fossil fuels are the primary energy sources for transport systems and accordingly, the emission of greenhouse gases especially carbon dioxide is accredited to transportation industry. Hence, it is impossible to ignore environmental requirements in the transit planning phase. In this study, we develop a bi-level and bi-objective optimization model to identify the optimum line frequencies. One of the objectives is to minimize the mean travel time of the passengers while the other objective is to minimize the total emission. The efficiency of the model is demonstrated with a case study on Istanbul bus network.

This study has the potential of being a starting point for many future researches. We can only conceive of apparent ones. As for example, the model can be extended to include limited capacity of the buses and the behavior of the passengers under congestion (SUE). Another line of research is to satisfy in-day and day-to-day demand by taking into account dynamic frequency assignment. Finally, instead of only optimizing line frequencies, the decision of adding new or discontinuing existing lines can be also formulated and added to the model.

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