# of Urban Public Transportation Considering the
ize: A Case Study from Palestine

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Abstract: We introduce a simple yet efficient approach to optimize the modal fleet size of urban public transportation services, considering both user- and operator-oriented factors. This is envisaged to enhance the potential for achieving sustainable urban transportation systems and, eventually, opportunities to create sustainable cities. The presented constraint optimization approach can be described as follows. First, the expected passenger demand and the cycle time for the public transportation service are estimated. Next, the desired constraints and parameters, such as those related to the headway and seat supply, are determined. Finally, the optimal combination of different vehicle classes and the number of trips satisfying all the defined constraints are determined. The case of an urban area in a developing country is considered. The resulting solution determines the optimal numbers of public transportation trips and vehicles, by mode, required to meet the expected passenger demand, provide a high-quality service with acceptable headways for passengers, and, at the same time, reduce the service providers' costs as well as the environmental impacts. It is also concluded that a fleet composed of different modes can better facilitate the achievement of the optimal solution for passengers and service providers compared with the one-mode fleet.

Keywords: constraint optimization; modal fleet size; sustainable transportation; public transportation planning

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1. Introduction

Public transportation is one of the principal components of any urban transportation system. It plays a key role in providing mobility for a considerable share of the population in any society in a sustainable manner. If public transportation does not satisfy the population's needs in a comfortable and suitable manner, transportation system problems may occur. Therefore, transportation engineers and city planners develop action plans to achieve efficient public transportation and sustainable urban systems.

The role of public transportation has been given increasing attention in urban transportation planning and operations, whether in developed or developing countries. An emerging developing country is targeted in this paper, where the proposed approach for optimizing urban public transportation services could serve as a model for other urban areas in developing countries that have common characteristics and challenges.

The public transportation sector in developing countries, in general, has faced several challenges and been affected by many problems. One of the most relevant problems in this context is the surplus or deficit of public transportation vehicles and/or trips for different routes due to the improper estimation of the passenger demand as well as the number and size of vehicles needed to meet this demand [1]. Moreover, in some areas, public transportation services do not run according to a fixed timetable or even clear operating hours, with these hours changing irregularly and without notice. Instead, vehicles depart the terminal once they are full of passengers. This can lead to unreasonably long headways and waiting times in the off-peak periods. Additionally, during the peak periods and seasons, service capacities cannot satisfy the demand, as the number and size of the vehicles are not well-studied, which results in relatively long headways, leaving passengers to wait at the stops for the next available vehicles. The illegal transportation of passengers using private cars for a fee is yet another problem, which also affects the accurate estimation of the actual passenger demand. All these problems, among others, lead to low-quality public transportation systems in developing countries, which require substantial measures and improvements in several aspects.

In this paper, we develop a simple yet efficient way to provide short- and medium-term solutions for an important number of the current issues affecting public transportation in urban areas. The developed approach takes into consideration several factors that can be divided into two main categories: (i) user-oriented factors, such as the quality or level of service, usually represented by the trip headway and trip frequency, and (ii) service-provider-oriented factors, such as owning and operating costs, which can be implicitly expressed by the number of transportation units/vehicles and number of trips. In addition, there are some other general factors that must be fulfilled during planning for public transportation services, including, for example, the fact that the supply offered by the service providers must at least meet the expected passenger demand.

This approach aims to determine the optimal number of public transportation trips and, accordingly, the number and size of public transportation vehicles needed to sufficiently meet the passenger demand, provide a high-quality service to the users, and, at the same time, save owning and operating costs due to un-needed or additional vehicles, as well as the running of unnecessary trips by the service providers. Unlike other optimization approaches, the presented approach is practical and does not require many detailed inputs, making it suitable for optimizing public transportation services in urban areas in developing countries with minimal data or effort required.

Determining the optimal number and size of public transportation vehicles can also serve as a step towards more sustainable transportation systems. For instance, replacing a large number of small vehicles (shared taxis) with a smaller number of larger vehicles (mini or standard buses) can help to reduce traffic congestion in urban road networks. Moreover, running public transportation vehicles based on fixed timetables and providing a satisfactory service with a high frequency and short headway will most likely result in demand shifting away from private cars. More people can then be attracted to the improved public transportation system and even non-motorized modes such as cycling and walking, and accordingly, this can help to mitigate traffic congestion, emissions and air pollution, as well as road noise. Thus, the approach overall objective is to achieve a win-win situation for all involved parties.

In order to achieve this optimized situation, the best combination of different vehicles must be found. This means that, sometimes, having different vehicle classes or modes (i.e., different vehicle sizes) in the fleet for a given route might be better than having a one-class fleet in order to achieve the optimal case. This depends on several factors, such as the passenger demand, desired headway, and route cycle time (i.e., the time needed for one transportation unit on a given route to make a round trip, including the layover/recovery time), as will be shown in the following sections.

The remainder of this paper is organized as follows. Section 2 briefly investigates the works most closely related to the problem at hand. In Section 3, the methodology followed in this paper, along with the optimization model, is described. Section 4 presents the case study used to test our approach, reporting and discussing the results. Finally, the main findings of this research and the recommendations are discussed in Section 5.

2. Related Work

Transport units or vehicles are among the fundamental components of public transportation services, which also include timetables, operating headways, the network structure, distance between stops, and fare policies [2]. The reasonable allocation of service capacity is the key to the successful operation and management of public transport systems.

Vehicle size and quantity are the two factors that should be considered in this context, and they have important and direct impacts on the efficient operation of public transportation and the quality of service as perceived by the users. This is part of a larger problem known as fleet management, where public agencies and private companies attempt to manage the operation of passenger or freight transportation services in order to serve the customer demand with the objective of cost efficiency [3]. In the field of urban public transportation, the problem is related to providing the users with a high-quality service while maintaining reasonable asset and operation costs for the fleet.

Many of the fleet management problems involved in public transportation, such as vehicle routing, scheduling, and network design, are complex combinatorial optimization problems. These problems are challenging to solve, even in static scenarios. The situation becomes even more complicated when considering real-time requirements. However, recent advancements in algorithms and computing technology have made it possible to handle such large combinatorial problems through reasonably effective approaches.

Several mathematical models and techniques have been developed for optimizing the operation of public transportation fleets, including graph and network algorithms, combinatorial optimization, and approximation algorithms, among others. For instance, a metaheuristic method was presented for optimizing public transportation networks, considering the route network design, vehicle headway, and timetable assignment [4]. The approach aims to identify a transit network that minimizes the passenger cost function for a given road network, passenger demand, and total fleet size. A constraint satisfaction model was proposed to optimize public transportation services [5]. While no objective function was determined, several types of constraints related to passenger demand, budget limit, and level of service were presented. More recent works have exploited automated data collection methods enabled by Intelligent Transportation System (ITS) applications and combined them with optimization models for more efficient public transportation planning and operation. For example, temporal demand patterns have been extracted using Automatic Fare Collection (AFC) data and incorporated into multi-period timetabling optimization models to account for demand variation over time [6,7]. More detailed and comprehensive reviews of the models and algorithms used in fleet management and public transportation optimization can be found in the relevant literature [3,8,9].

More closely to the problem at hand, the optimal size and type of public transportation vehicles have also been well-studied in the literature. Some studies, especially those conducted in the past, concluded that small vehicles have several benefits and advantages over larger ones, such as the ability to offer faster trips and shorter headways [10,11]. However, this might have significant, adverse impacts on traffic congestion and the environment. More recently, some works were conducted to build mathematical and optimization models aiming to address this issue. For instance, an optimization model was developed for fleet sizes considering monetary constraints [12]. Another study proposed an optimization model with capacity constraints to determine the fleet size and service frequency for public transportation routes [2]. An optimization method was presented to design and determine the size of the vehicles and headways while minimizing the costs of both users and operators [13]. The peak and off-peak periods of public transportation were considered in another study to help to identify the optimal fleet size, vehicle capacity, and trip frequency [14]. Finally, a modeling framework using mixed-integer stochastic programming was proposed to determine the optimal bus fleet size and assign buses to multiple routes, considering an uncertain demand [15].

It can be noted that the previous research mainly attempted to solve this problem and identify the optimal number of vehicles for public transportation routes by assuming a one-vehicle class fleet. In contrast, in this paper, we consider the differences between several public transportation modes in terms of the headway, cycle time, and capacity to identify the optimal combination of a multi-vehicle-class fleet. This combination will minimize the overall number of vehicles and trips needed to sufficiently meet the expected demand and therefore reduce the service providers' costs and increase vehicle utilization.

At the same time, the optimal solution will provide a high-quality service to the users with reasonable headways and offer flexible alternatives to better suit users' preferences.

3. Methodology

We present an approach that can be used to optimize the number of public transportation vehicular trips and, accordingly, the vehicles needed to serve the passenger demand while maintaining a high-quality service for the users. This approach is practical, does not require many inputs, and is thus suitable for optimizing public transportation services with minimal data or effort required. It is also generic and can be applied to any public transportation mode, including both road-based and rail-based public transportation. The presented approach can be divided into four steps. First, the expected passenger demand for each route in the design year is estimated. Second, the initial cycle time for each route is calculated. Next, the desired constraints and parameters, such as the maximum headway and maximum seat supply, are determined. Finally, the optimal combination of different vehicle classes and number of trips required are determined based on the given inputs and constraints.

The expected passenger demand for a given route can be defined as the number of passengers expected to use this route for a given unit of time (e.g., hour or day) in the design year. This can be estimated by firstly determining the current demand, which can be obtained using different methods, such as conducting interviews with service providers, analyzing the origin–destination (O-D) matrix, if there is one, or counting all the incoming and outgoing vehicles at the terminals for all the routes. Next, the expected future demand for the design year can be projected based on the obtained current demand using a proper growth rate and number of years from the current year to the design year. It is also possible to multiply the future demand by a factor representing the expected demand shift from the private vehicle modes as a result of improving the public transportation system.

Next, the initial cycle time for each route and each vehicle class is calculated, noting that different vehicle classes (e.g., shared taxis, minibuses, and standard buses) can have different operating speeds and thus different cycle times. This can be achieved by calculating the total time needed for a given transportation unit (U) to travel from the first stop (A) on a given route to the last stop (B) and then the other way around, from B to A, in addition to the recovery/layover time for both stops B and A, respectively, until the unit U is ready to travel again from A to B in the next trip, as shown in Figure 1.

Figure 1. Cycle time concept.

The travel time can be calculated by dividing the route length (from the first stop to the last stop) by the average operating speed, which can be defined as "the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed" [16]. The operating speed may be different from one route to another based on several factors, such as the traffic volume, road geometry, signal density, and access density [17]. On the other hand, the recovery time can be defined as the time that a transportation unit spends at the route terminal (first or last stop). There are several reasons for providing this time, such as recovery from delays incurred in travel, the adjustment of the schedule to maintain a uniform headway, and the need for rest on the part of the crew [17]. The recovery time can be assumed to be a percentage of the travel time (e.g., 15%) [17].

Before forming the objective function and solving the optimization problem, a few parameters should be set. Such parameters include the maximum headway and maximum seat supply. The headway can be defined as the time interval between two consecutive vehicles departing from a given stop and serving on the same route [18]. The maintenance of regular and relatively short headways has been identified as a key indicator of public transportation service quality and reliability [19,20]. According to the Transit Capacity and Quality of Service Manual [21], a frequency of three to four vehicles per hour leads to an acceptable public transportation service as perceived by passengers. Therefore, the maximum desirable wait time for public transportation (i.e., trip headway) varies between 15 and 20 min.

As for the seat supply, it can be defined as the total number of seats provided for a specific public transportation route per unit of time. Clearly, the seat supply should be at least equal to the passenger demand. However, as the passenger demand might be variable, especially on seasonal occasions, the seat supply should be at least moderately higher than the passenger demand (e.g., 25% more than the passenger demand). At the same time, offering more seats than required can have adverse impacts, especially from a service provider point of view, such as additional, unnecessary owning and operating costs for large vehicles or the running of more trips than required. Therefore, a maximum seat supply should be set, which might be understood as a factor of the minimum supply itself.

Finally, after determining all the inputs and parameters, the objective function can be formulated and optimized. In optimization, the "best" element, with regard to some criteria, is selected from a set of available alternatives [22]. In a generic case, an optimization problem aims to maximize or minimize a real function, the objective function, by computing and comparing the value of the function based on systemically chosen input values that belong to a permitted set [23]. A special case is constrained optimization, where constraints are imposed on the variables. Constraints may be in the form of equality constraints, where some variables must be equal to predefined values, or inequality constraints, where the variables must be equal to or greater/less than the predefined values.

In this paper, the objective function is formulated based on the minimization of the total number of trips (which is associated with the total number of vehicles), as shown in Equation (1). This variable was chosen because we believe that it is the most critical variable in this problem from several perspectives. For instance, although the average headway is a key performance indicator of the public transportation service, it is most likely that passengers will not mind waiting for an additional one or two minutes. In other words, the consequences and impacts of increasing one unit of headway is not as critical or serious as increasing one unit of the total number of trips or transportation vehicles. In the latter case, any increment will result in substitutional costs for service providers and even the road network as a whole (in terms of traffic congestion, for example). Nevertheless, in order to guarantee a maximum headway value that should not be exceeded, in this case, an inequality constraint is used. Note that minimizing the total number of vehicles needed leads to the same result, as it is dependent on the number of trips.

$$Min\ Z = \sum_{i=1}^{n} T_i \tag{1}$$

which is subject to

$$a.D \leq S \leq a.D.b$$

$$H_{i+1} \geq H_i \text{ and } C_{i+1} > C_i \ \forall\, i \in \{1 \ldots n-1\}$$

$$H_{avg} \leq H_{max}$$

where $Min\ Z$ is the objective function that aims to minimize the total number of trips needed, T_i is the number of trips per unit of time needed for a given public transportation route (trips/h), i is a certain vehicle class, n is the number of vehicle classes available to choose from, S is the total seat supply (seat/h), D is the estimated passenger demand (pax/h), a and b are decimal coefficients greater than or equal to 1.00, H_i is the headway for vehicle class i (min), C_i is the capacity of vehicle class i (seat), H_{avg} is the weighted average headway for all vehicle classes, and H_{max} is the maximum desirable headway.

Coefficients a and b must be set carefully to guarantee the consideration of demand fluctuations and simultaneously prevent the provision of too many vehicles and trips, respectively. For practical reasons, the headway of small vehicles must be shorter than that of larger vehicles. Moreover, the headway and the numbers of vehicles and trips for a given vehicle class must have reasonable upper and lower bounds (domain). For example, the number of trips per hour for a specific vehicle class can range from 0 (no trips needed) to 60 (one trip every minute), and so on. Algorithm 1 shows the pseudocode for the optimization model used in this approach.

Algorithm 1 To Find the Optimal Combination of Public Transportation Fleet Vehicles

Input: *Passenger demand (D), initial cycle time (CT_i), and capacity (C_i) for each vehicle class i*

Output: *Optimal number of trips (T_i) and other dependent variables for each vehicle class i*

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Initialization of variables and setting upper and lower bounds: Ti, number of vehicles (Vi)
and headway (Hi) for each vehicle class i
Introducing constraints: Hi+1 ≥ Hi and Ci+1 > Ci ∀ i ∈ {1…n−1}
                    Havg <= Hmax
                    S >= Smin
                    S <= Smax
 While (ΣTi is not optimal or all constraints are not satisfied)
     | For (i in 1…n)
     |     | Ti = t              // assign a new value to number of trips
     |     | Hi = 60/Ti          // update headway
     |     | Vi = CTi/Hi         // update number of vehicles
     | End for
     | S = Σ(Ti * Ci)            // update seat supply
     | Havg = Σ(Ti * Hi) / ΣTi   // update average headway
     | ΣTi = Ti + Ti+1 + … + Tn  // update total number of trips
 End while
 Return Ti, Vi, and Hi           // return optimal variables for each class
 End
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4. Case Study and Results

The case study considered in this paper to illustrate the development and application of the proposed optimization of urban public transportation services is the Nablus Urban Area located in the developing country of Palestine.

For decades, public transportation in Palestine has consisted of three modes: buses (vehicles of 19–50 seats operating on fixed routes), shared taxis (vehicles of 4 or 7 seats operating on fixed routes), and private taxis (i.e., vehicles of 4 seats for individual point-to-point trips). In addition, part of the public transportation demand is met by illegal private vehicles for a fee [24]. Since the establishment of the Palestinian National Authority (PNA) in 1994, there have been almost no major developments in the public transportation system as a result of the fact that this system is completely owned and operated by the private sector (firms or individuals) [24]. Therefore, the PNA mainly depends on private sector initiatives to develop and improve the public transportation system [25]. The role of the Ministry of Transportation (MOT) in this regard is limited to the regulation of public transportation services through setting relevant policies, granting permits for the operation of public transportation routes and vehicles, determining the maximum number of vehicles allowed to operate on each route, and defining the service fares [24]. However, for different reasons, the monitoring and control of these services by the MOT have been weak.

The Nablus Urban Area consists of Nablus City, one of the largest and most vital cities in Palestine, and 13 neighboring Local Government Units (LGUs), namely, Beit Wazan, Zawata, Beit Iba, Deir Sharaf, Qusin, Sarra, Tell, Iraq Burin, Kafr Qallil, Rujeib, Salim, Deir Al-Hatab, and Azmut. Figure 2 shows the study area along with its public transportation routes [26]. The study area is defined based on a recent World-Bank-funded project, Integrated Cities and Urban Development (ICUD), which aims to strengthen the institutional and technical capacities of the participating urban areas in order to plan for sustainable urban growth. The project considers the five largest Palestinian urban centers, including Nablus City and the surrounding suburbs and villages.

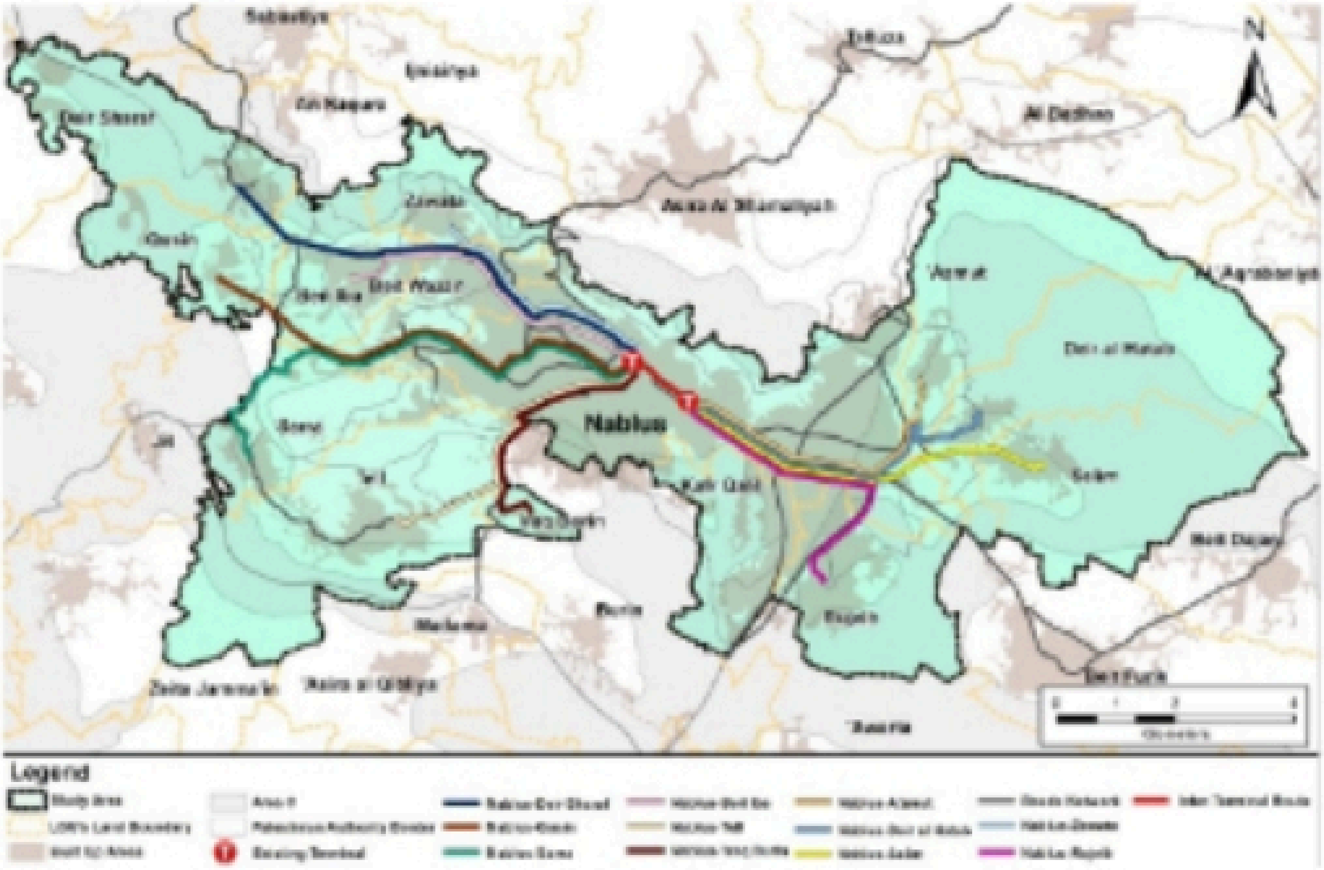

Figure 2. Map of the public transportation routes in the study area.

The public transportation connecting each LGU with the Nablus Central Business District (CBD) includes shared taxis and/or bus routes, together forming a small radial network with Nablus City as its center. The only exceptions are Beit Wazan and Kafr Qallil, where private vehicles illegally transport passengers between these areas and Nablus CBD for a fare. Note that we consider only shared taxis and buses in this case study, as these are the only modes available in the study area. However, the same approach can be extended and similarly applied to the other modes, including rail-based public transportation. It should also be noted that although all the routes in the case study area connect two regions, the proposed approach is still applicable to cases where a given route also passes through intermediate regions, since what matters is the total passenger demand for that route. Nevertheless, special attention should be given to cases where the demand is estimated using an O-D matrix, as the considered demand would be partial, excluding the demand between the origin and the intermediate regions.

There are two classes of shared taxi vehicles that were observed in this network. Most of the shared taxi routes operate seven-passenger vehicles, except for Beit Iba–Nablus and Zawata–Nablus routes, where four-passenger vehicles operate instead. Moreover, the Nablus–Qusin route is not served by shared taxi vehicles. For bus routes, Nablus–Qusin and Nablus–Rujeib are the only two bus routes in the network, where 19-passenger and 50-passenger buses serve the routes, respectively. Note that the current fleet of each route consists of one vehicle class only, unlike the proposed fleet, which can have multiple vehicle classes for each route.

The total passenger demand for each route using the shared taxi and/or bus service was obtained from a detailed public transportation study conducted in 2019 as part of the ICUD project [26]. The study consisted of both field surveys and interviews with the service providers in the study area. The collected data included the number of available vehicles, service frequency, and ridership rate, among other factors, for each route. As there are no public transportation routes connecting Beit Wazan and Kafr Qallil with Nablus City, the respective demand for public transportation was estimated based on the analysis of an O-D matrix for the Nablus Urban Area obtained from the ICUD study report [26]. The estimated future passenger demand for the year 2027 (i.e., five years from the present as a form of short-term planning) was projected from the 2019 data assuming a growth rate of 4% [26]. In addition, based on the same study [26], it was assumed that 10% of the total demand (i.e., that obtained from the same O-D matrix) will shift from the private car mode to the public transportation mode as a result of the improvement of the latter. Finally, to account for unexpected demand increase (e.g., during seasonal occasions or peak periods), a factor of 1.25 was used to further increase the future demand [26], which can also be called the minimum seat supply. Note that the applied value of this factor is a rough estimation, and other values may be used instead.

The initial cycle times for each route and for each vehicle class were calculated based on the actual length of each route, assuming operating speeds of 20, 25, and 30 km/h for the 50-passenger, 19-passenger, and 7-passenger vehicles, respectively. A recovery time of 15% of the two-way travel time was also considered for each cycle time [17]. It is worth mentioning that the four-passenger vehicle class was eliminated from the list of the possible vehicle classes for the future analysis in order to reduce traffic congestion. Table 1 reports the current passenger demand, length, and initial cycle time for each route in the network.

Table 1. Current passenger demand, length, and cycle time for each route.

Route	Current Demand (pax/h)	One-Way Route Length (km)	Cycle Time for 7-Pax Class (min)	Cycle Time for 19-Pax Class (min)	Cycle Time for 50-Pax Class (min)
Nablus–Beit Wazan *	100	6.1	29	34	43
Nablus–Zawata	102	4.7	22	26	33
Nablus–Beit Iba	57	5.3	25	30	37
Nablus–Deir Sharaf	31	8.3	39	46	58
Nablus–Qusin	39	8.5	40	47	59
Nablus–Sarra	49	9.6	45	53	67
Nablus–Tell	64	7.3	34	41	51
Nablus–Iraq Burin	15	5.0	23	28	35
Nablus–Kafr Qallil *	69	4.3	20	24	30
Nablus–Rujeib	113	4.9	23	28	34
Nablus–Salim	85	7.8	36	44	54
Nablus–Deir Al-Hatab	31	6.6	31	37	46
Nablus–Azmut	34	6.9	32	39	48

* The current passenger demand is estimated from the O-D matrix.

For the optimization constraints, 15 min is used as the maximum acceptable average headway based on the aforementioned value recommended by the Transit Capacity and Quality of Service Manual [21], and a factor of 1.1 is applied to determine the maximum seat supply permitted in the model compared to the adjusted future demand (i.e., the minimum seat supply). Note that the value used here for the maximum seat supply factor is merely an assumption, and other values could be used instead.

Finally, these values from Table 1 are input into the optimization model to identify the optimal combination of different vehicle classes needed for each route using the MiniZinc constraint modeling language. This combination is guaranteed to reduce the total number of trips and, accordingly, the vehicles needed for each route while maintaining a high-quality service by offering acceptable average headways and satisfying the expected future demand.

The final output of the algorithm includes the number of trips, number of vehicles, and headway of each vehicle class for each route. Table 2 summarizes the results of the model for some randomly selected routes. For each route, the optimal fleet combination with the lowest possible number of total trips and vehicles which, at the same time, offers a reasonable supply satisfying the future demand and provides an acceptable average headway for the users is identified.

Table 2. Results of the optimization model for some routes.

Route		Nablus–Zawata	Nablus–Beit Iba	Nablus–Qusin	Nablus–Tell	Nablus–Rujeib	Nablus–Salim
Number of Trips/h	7-pas veh	4	-	5	6	-	-
	19-pas veh	-	7	3	-	-	-
	50-pas veh	4	-	-	2	5	4
Headway (min)	7-pas veh	15	-	12	10	-	-
	19-pas veh	-	8	20	-	-	-
	50-pas veh	15	-	-	30	12	15
Number of Vehicles	7-pas veh	2	-	4	4	-	-
	19-pas veh	-	4	3	-	-	-
	50-pas veh	2	-	-	2	5	4
Total Supply (seat/h)		228	133	92	142	250	200
Future Demand * (pass/h)		218	122	84	137	243	183
Average Headway (min)		15	8	15	15	12	15

* The future demand takes into consideration the annual growth rate, the shift in demand from the private vehicle mode, and the unexpected demand increase.

To evaluate the efficiency of the approach, a comparison of the public transportation routes between the current situation [24] and the optimization-model-based situation was conducted. The average headway and total seat supply attributes were used in the comparison to assess the quality of service for each route, whereas the total required number of vehicles attribute was used to examine the overall cost for the service provider. Figures 3–5 show comparisons between the current (before) and model-based (after) situations for the average headway, number of vehicles, and seat supply, respectively. Two LGUs (i.e., Beit Wazan and Kafr Qallil) are omitted from these figures due to the lack of data on public transportation for the current situation, as previously illustrated.

According to Figure 3, it can be noted that the average headway is clearly reduced for most of the routes, excepting a few routes; however, these still have acceptable headways (i.e., satisfying a maximum desirable headway of 15 min).

For the number of vehicles, based on Figure 4, it is clear that number of vehicles required to serve each route is significantly lower than the current number of vehicles, except for three routes. Two of them have the same number of vehicles (Nablus–Deir Al-Hatab and Nablus–Deir Sharaf), while one route has more vehicles (Nablus–Qusin), as it is currently affected by a lack of vehicles, with only one operating vehicle.

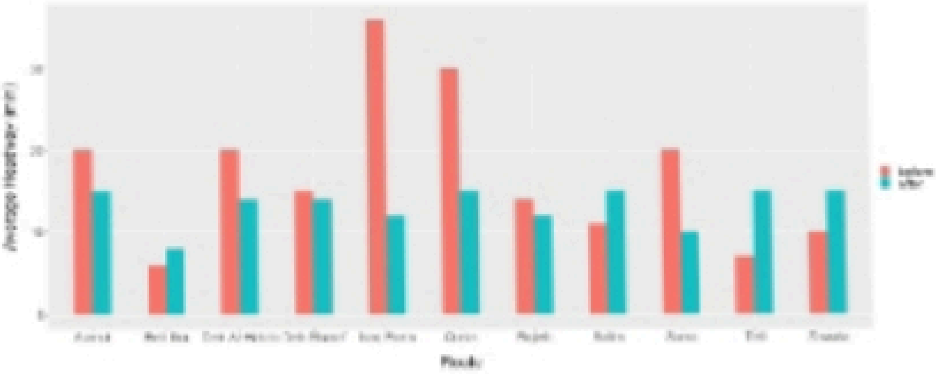

Figure 3. Average headway comparison between current and future situations.

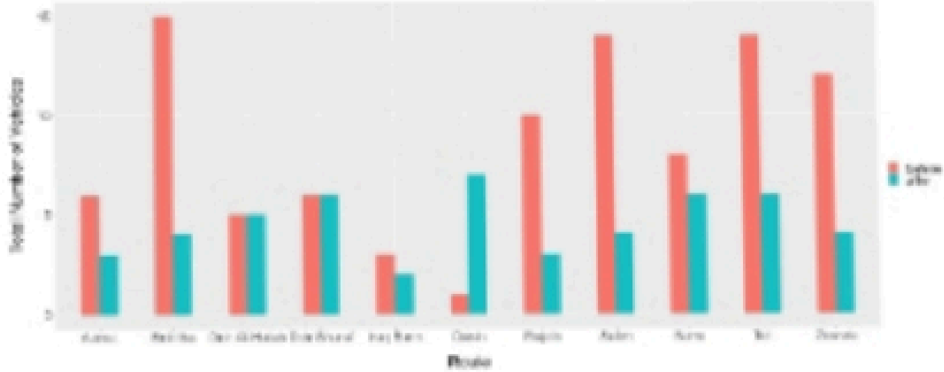

Figure 4. Comparison of total number of vehicles between current and future situations.

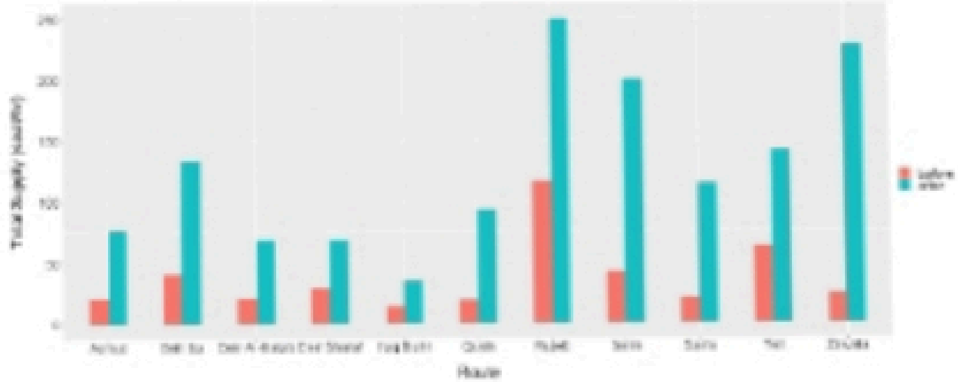

Figure 5. Comparison of total seat supply between current and future situations.

As indicated in Figure 5, the total seat supply is higher for all the routes in order to satisfy the increasing passenger demand, which will grow over time. In addition, a demand shift of 10% from private vehicles to public transportation vehicles is considered. It can also be noted that although the expected demand in the design year used in the model is almost twice that of the current demand, the model results still have significantly lower numbers of vehicles needed, with better or at least similar headways, compared with those in the current situation.

Overall, it can be concluded that the results from the optimization model are much better for all involved parties. For passengers, the level of service will be improved with shorter or at least acceptable headways and a sufficient seat supply. On the other hand, the overall owning and running costs of the vehicles will be significantly lower for the service provider (i.e., with a smaller fleet size) while satisfying the passenger demand at the same time. For the transportation system as a whole, replacing a large number of small vehicles with fewer larger vehicles will have positive impacts on the network in terms of reducing traffic congestion and environmental impacts.

The environmental impacts of the optimized system were evaluated in terms of the carbon footprint for travel. It was expected that the optimal system, which has shorter headways, higher capacities, scheduled departures, and modern vehicles, will encourage more people to use the public transportation system, resulting in a demand shift from the private car mode.

To estimate the carbon footprint for the optimized scenario, the expected future hourly ridership (i.e., number of users) for each vehicle class on each route was estimated using the future demand, assuming an 80% vehicle occupancy rate. Next, the carbon footprint per kilometer of travel was calculated based on the average carbon dioxide (CO_2) emissions per passenger kilometer for each vehicle class, as shown in Table 3 [27]. Finally, the emissions produced by each vehicle class were added together and multiplied by the length of each route to compute the total carbon footprint for each route. For the current situation, the same procedure was followed to calculate the emissions produced by the existing public transportation vehicles for each route. In addition, the difference in ridership between the future and current situations (i.e., shifted demand) was considered in the emission calculations for the current situation as the current private car users. For these users, the carbon footprint is estimated based on the average CO_2 emissions per passenger kilometer for the private car mode, as shown in Table 3 [28], assuming an occupancy rate of 1.7 passengers per vehicle [29]. Table 4 shows the CO_2 calculations for a sample route.

Table 3. CO_2 emissions for different vehicle classes.

Vehicle Class	Capacity (pax)	Fuel Type	CO_2 Emissions (g/km)	CO_2 Emissions (g/pax km) when 80% Full
Shared Taxi	4	Petrol	179 [28]	56
Shuttle Bus	7	Diesel	209 [27]	37
Minibus	19	Diesel	630 [27]	41
Standard Bus	50	Diesel	1350 [27]	34
Private Car	4	Petrol	179 [28]	105 *

* Considering an occupancy rate of 1.7 pax/car.

Table 4. Sample CO_2 calculations for Nablus–Tell route.

	Optimized (Future)			Current	
Vehicle Class	Shuttle Bus	Minibus	Std. Bus	Private Car	Shuttle Bus
Capacity	7	19	50	4	7
Trips/h	6	-	2	37 *	9
Ridership/h **	33.6	-	80.0	63.2	50.4
CO_2 (g/pax-km) ***	37.3	41.4	33.8	105.3	37.3
CO_2 (g/km)	1254	-	2700	6656	1881
Route length (km)	7.3	7.3	7.3	7.3	7.3
CO_2 (kg/h)	9.2	-	19.7	48.6	13.7
Total CO_2 (kg/h)		28.9		62.3	

* Based on the public transport ridership difference between the two scenarios. ** Considering an occupancy rate of 80% for public transport vehicles and 1.7 pax/car for private cars. *** From Table 3.

The total CO_2 emissions per hour of operation for each route in both the current and future situations are presented in Figure 6. The rate of change in CO_2 emissions slightly different from one route to another depending on the fleet combination for each route in both the current and future situations. The grand total values of CO_2 emissions for the whole network in the current and future situations were found to be 810.3 and 331.5 kg per operation hour, respectively. This means a total reduction of 478.8 kg per hour, which is equivalent to 59.1% of the CO_2 emissions in the current situation. This is a considerable amount given the small size of the public transportation network in the study area. In cases where hybrid or electrical vehicles are used in the optimized scenario, the savings will be even more significant.

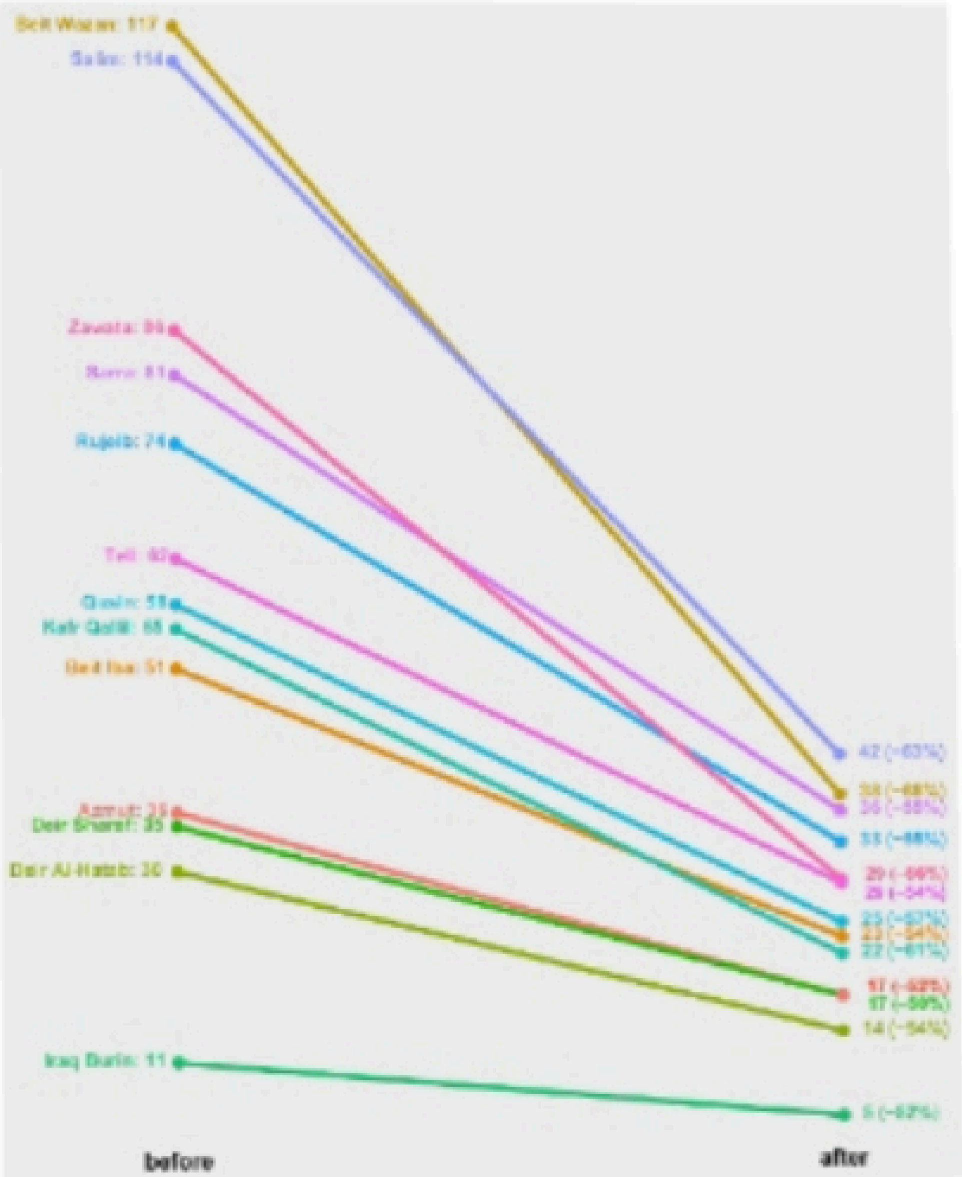

Figure 8. CO_2 emissions (kg/h) for each route in the current and future situations.

5. Conclusions

Public transportation services in many regions, especially developing countries, still face serious issues and challenges, such as a low level of service, lack of adherence to fixed timetables, and a deficit or surplus of transportation units, mainly resulting from poor planning for this vital sector.

In this paper, we introduced an optimization-based approach to identify the optimal combination of vehicle classes needed to efficiently run public transportation services. The approach is simple, allows for fleets with multiple vehicle classes, and does not require many inputs compared to other optimization models but provides optimal solutions satisfying the needs of both operators and users, making it an ideal choice for cases with limited available data, especially in urban areas in developing countries. The presented approach was tested on a small public transportation network in the Nablus Urban Area in Palestine.

The findings show that this approach can provide optimal solutions which satisfy the objectives of a high level of service for passengers in terms of headway, along with the objectives of low overall costs for public transportation service providers in terms of the numbers of vehicles and trips. Such solutions can also help to achieve a more sustainable transportation system through reducing traffic congestion, carbon footprints for travel, and road noise. We also concluded that having a fleet consisting of multiple vehicle classes which have different characteristics for each route can help to ensure the optimal situation for all parties compared to the one-class fleet, for which efforts have traditionally been concentrated on the optimization of the operation of one public transportation class. The presented approach can also help to offer alternative vehicle classes for users, probably with a flexible fare structure, in order to better match their preferences.

Our recommendations include considering the potential for extending the approach to take into account the capital and operational costs of the public transportation modes (i.e., rolling, personnel, and fixed costs), as the current approach considers these factors indirectly through the optimal number of vehicular trips associated with the number of vehicles for each mode. The model could also be improved by minimizing the total system costs by including user costs, such as service the fare and detailed travel time, as well as environmental costs, such as the carbon footprint, in the objective function, in addition to the operator costs. In addition, it is recommended to consider the sensitivity of changes in key variables, such as modal speeds and dwell/layover times, to allow for refined optimal solutions. Finally, it is recommended that future work extends and tests the presented approach on scalable public transportation networks with different modes, such as rail-based public transportation. It would also be interesting to implement other optimization approaches and compare their results against the results obtained from the presented approach.

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