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DOI
10.1016/j.cstp.2020.05.001

Publication date
2020

Document Version
Final published version

Published in
Case Studies on Transport Policy

Case Studies on Transport Policy 8 (2020) 946–953

Contents lists available at ScienceDirect

Case Studies on Transport Policy

journal homepage: www.elsevier.com/locate/cstp

Designing bus rapid transit systems: Lessons on service reliability and operations

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ARTICLE INFO

Keywords:
Bus rapid transit
Service reliability
Transit operations

ABSTRACT

Cities worldwide are looking for expanding the capacity of their public transport system while considering budget limitations. Bus Rapid Transit (BRT) systems are increasingly considered as alternatives for designing a mass public transport in mid-size cities in developed countries. While operations have been recognized as an important success factor, previous studies have focused on infrastructure design and planning principles of BRT. We study the operations of BRT related to service reliability and service utilization and derive lessons for planning and operations. The study is centered on the performance of the Matronit BRT system in Haifa, which is the first mass transit network of its kind in Israel. The inter-relation between service reliability, fleet management and service utilization are analysed. The speed and reliability improvements attained by the infrastructure and technological priority measures need to be complemented with control instruments to yield further gains for both service users and service provider.

1. Introduction

Bus rapid transit (BRT) systems have emerged as an alternative design for high-level of service systems in the past two decades. BRT systems first flourished in cities across Latin America (Hidalgo and Graftieaux, 2008) before spreading to south and east Asia and then throughout the globe (Hidalgo and Graftieaux, 2013). BRT systems offer a high-capacity alternative to rail-bound systems which require significantly higher investments and a longer implementation time, as concluded by Deng and Nelson (2011) in their review. In large cities in emerging economies, primarily in Latin America and South Asia, BRT is an integral part of the mass public transport network or constitute the main part of this system. In contrast, BRT implementation in developed economies, has been primarily confined to mid-size cities where demand level does not justify large investments in urban rail infrastructure. In the European context, these projects are sometimes referred to as Buses with High Level of Service (BHLS) (Finn et al., 2010).

BRT systems exhibit a considerable variation in their design and execution. Notwithstanding, key design features of BRT systems include their right-of-way, distinguished stations and vehicles, speedy fare collection and intelligent transport systems functionalities, in particular real-time fleet management and traffic signal priority capabilities. In sum, the design principles aim to increase system capacity, give it priority over car traffic, integrate it with other public transport and non-motorized modes and profiliate it as a metro-like service. For a detailed review of their characteristics, see Jarzab et al. (2002), Levinson et al. (2003) and Deng and Nelson (2011). These measures are geared towards increasing service speed, reliability, visibility, and ultimately ridership. The overall approach aspires to develop a bus service that offers qualities associated with rail-bound services such as light rail or metro. Several studies examined the impact of BRT on ridership levels (Levinson et al., 2002; Currie and Delbosc, 2011; Hensher and Li, 2012) and travellers' perceptions (Deng and Nelson, 2012). Mulley et al. (2014) performed choice experiments to estimate traveller preferences toward BRT and light rail transit (LRT). Results from these studies concur with the travel satisfaction literature (e.g. Susilo and Cats, 2014), suggesting that service speed and reliability are the most important service attributes in shaping travellers' perceptions.

Attaining a higher speed and reliability depends on a range of variables and measures which relate to infrastructure and management. Hensher and Golob (2008) perform a comparative assessment of 44 BRT systems worldwide based on system-wide design, ridership and cost attributes. These studies have contributed to the growing understanding of the main ridership drivers related to BRT and overall system performance in relation to key design variables such as distance between stops, line length and peak headway. In addition to a proper

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https://doi.org/10.1016/j.cstp.2020.05.001
Received 1 March 2018; Received in revised form 2 April 2020; Accepted 1 May 2020
Available online 05 May 2020
2213-624X/

design of the BRT system, the operational planning of BRT systems is critical in ensuring its performance, especially given the high service frequency and passenger demand. Previous studies have often focused on high-level, average and aggregate service indicators, assuming that an adequate design of the BRT system results in reliability improvements but lacked empirical underpinning as highlighted by Currie (2006) and Deng and Nelson (2011). Several traffic simulation models have been proposed for evaluating the operations of BRT service features such as right-of-way, boarding from all doors policy and headway-based operations (Abdelghany et al., 2008; Toledo et al., 2010; Ingvardson et al., 2017; Fadaei and Cats, 2016; West and Cats, 2017).

Our study contributes to the growing international experience with the development and evaluation of BRT systems in various contexts. Mallqui and Pojani (2017) contrasted the cases of BRT developments in Lima and Brisbane which they considered characteristic of a developing megacity with scarce resources and high public transport dependency, and a developed sprawling car-oriented city which lacks an attractive rai-based service, respectively. In this study, we report empirical findings from the implementation of a BRT system in Haifa, Israel. A unique feature that makes this case study of particular interest is that while Israel is a developed country, the BRT system in the focus of this study is not only the first BRT system in the country but also the first mass transit network in the country (i.e. there is a single urban rail line, a light rail, in Jerusalem).

In our analysis, we focus on design and operational aspects related to service reliability and service utilization, aspects that have been relatively understudies insofar, and derive lessons for planning and operations. In the analysis of the case study we do not limit the discussion to the performance as measured at a given selected moment but also share the experiences gained and shed light on the (often far from ideal) technical, planning and organizational processes associated with the planning and operating a new BRT system and that have led to the reported outcome. The field observations and performance analysis highlight the success and drawbacks of the Matronit implementation and on-going operations.

An overview of the case study which is in the focus of this research is provided in the next section. This is followed by an empirical analysis of service reliability, fleet management, on-board crowdedness and travel satisfaction, each of which accompanied with a discussion of the underlying factors and related planning perspectives and measures for service improvements. The paper concludes with a discussion of the key lessons for BRT planning and operations.

2. Haifa BRT system: from plans to operations

Haifa is the third largest city in Israel with a population of about 280,000 residents[1]. The city is located on the slopes of Mount Carmel and around the Haifa Bay, resulting with substantial slopes as the city ranges from sea level along the Mediterranean plains > 400 m above sea level on the Carmel. These differences in elevation pose a challenge in designing an efficient and effective public transport network with many of the neighborhoods being connected only through the mountain ridge. This has led to a decentralized urban structure with a large number of sub-centers. The Port of Haifa located in the center of the Haifa Bay and is the largest in the country. The population of the urban agglomeration area centered around Haifa amounts to 600,000, about half of which reside in the municipalities stretching along the northern part of the Haifa Bay. This agglomeration is the core of a larger metropolitan area with a total of approximately 1 million inhabitants. The regional transport authority estimates that 35%[2] of the trips in the metropolitan core are performed by public transport, decreasing to 24% when considering the entire metropolitan area.

The public transport network consists of urban and regional bus lines, a single underground funicular line that connects the downtown center to the Carmel center and seven train stations with suburban and national connections. The first master plan for Haifa Metropolitan area was published in 1996 by Yefe Nof Company[3]. One of the projects envisioned in the master plan was a light rail train (LRT) connecting the suburbs with Haifa CBD. In 2003 a decision was made to develop instead a BRT system, publicly branded as “Light Rail on Rubber Wheels”. The main arguments for making this change in plans were: (i) a reexamination of the demand led to the conclusion that the costs involved in the construction of an LRT line cannot be justified; (ii) substantial cost differences between the BRT and LRT alternatives; (iii) an increasing popularity of the BRT concept among planning circles, and most importantly; (iv) foreseen long and uncertain statutory and legal process required for realizing the LRT plan, unlike the BRT which utilizes existing road rights.

For the first time in Israel, the “Matronit” Haifa bus rapid transit system started to operate in summer 2013. The Matronit system consists of three lines which connect the Haifa downtown business district to the northern suburbs and the southern limits of the city (Fig. 1). The system connects the primary activity centers located along the Haifa bay area including seaside activity centers, the German Colony, the downtown business district, the port and key shopping centers. The Matronit has its own right-of-way in the form of exclusive bus lanes for the vast majority of its network instead of operating in mixed traffic which includes a high share of trucks due to port logistics.

The BRT network includes 143 stops, including four stops that offer interchanging to the train network. Line 1 is the longest, most frequent, has the highest share of segregated priority lanes, and serves the largest number of stops and passengers. Lines 2 and 3 serve urban arterials crossing through the municipalities to the east and north-east of Haifa. Line 3 also penetrates into a civic and commercial activity center using exclusive bus streets. The main axis between the key shopping centers, the port and the main metropolitan and regional bus terminal and train stations is served by all three BRT lines allowing also transferring within the Matronit system.

Table 1 summarizes the main characteristics of the lines. The high-frequency service operates with a planned headway of 4–6 min during the morning and afternoon peak periods and headways of 5–10 min during the rest of the day. The distance between stops is approximately 600 m on average. The vast majority of the BRT routes are separated from the rest of the traffic, ranging from 84% for Line 3 to 96% for line 1. Line 1 operates non-stop 24/7 and lines 2 and 3 have a wide service span operating from 5:00 to 00:30 and 00:00, respectively. Line 1 is also the busiest line in terms of daily ridership. The fleet consists of 100 articulated buses with 44 seats and a total design capacity of 80. The Matronit services are designed to improve stop operations by allowing for boarding from all (four) doors and at stop pre-boarding ticket purchasing and validation, hence alleviating drivers from handling payments. The characteristics of the lines are employed in the metrics used for quantifying service reliability (i.e. the coefficient of variation of the headway) and service utilization (i.e. volume – capacity ratios).

The introduction of the BRT service was accompanied by a major overhaul to the existing bus network with the objective to adjust the bus network to the new BRT lines so that an integrative system is offered. Changes included the cancelation of overlapping routes, rerouting competing lines, launching new feeder and urban routes, increasing the frequency of feeder routes, extension of routes and turning them into feeders and extension of service span. The overhaul involved changes to a total of 55 routes.

Each BRT vehicle is equipped with an automatic vehicle location (AVL) device, automatic passenger counter (APC) and signal priority

[1] Israel Central Bureau of Statistics – 2018 data.

[2] The Strategic plan of Developing Public Transport, Ministry of Finance & Ministry of Transport, 2012 [In Hebrew].

[3] Yefe Nof - Transportation, Infrastructure Constructions LTD.

Fig. 1. Matronit Bus Rapid Transit network in Haifa's urban agglomeration area. Source: Yefe Nof, Transportation, Infrastructure Constructions LTD.

Table 1
Key characteristics of the Matronit lines.

	Line 1	Line 2	Line 3
Length [km]	25	18	16
Exclusive bus lanes [%]	96%	84%	92%
Number of stops	41–42	26–27	28
Average distance between stops [m]	~600	~680	~570
Planned headway [min] (peak; day)	4; 5–6	6; 7–8	5; 7–10
Total number of departures per day	448	262	250
Total number of passengers boarding per day	~49,000	~18,000	~25,000
Service span	Non-stop	05:00–00:30	05:00–00:00

transmitters. Archived data from all trips performed during May 1- June 20, 2017 is analyzed in this study. Each entry in the dataset corresponds to a vehicle stop visit and contains the following fields: line id, trip id, stop id and name, date, door opening time, door closing time, number of boarding passengers, number of alighting passengers and the number of passengers on-board. These databases have been processed to obtain a series of service performance indicators. In the following we discuss our metrics and respective findings for each of the service performance dimensions.

3. Service reliability: combating bus bunching

Reliability is one of the most important attributes of quality of transit service and persistently among the most important service quality issue for both passengers and public transport agencies and operators (Eboli and Mazzulla, 2009; Abenoza et al., 2017). In the context of high frequency services where passengers arrive at the stop without consulting the timetable, passengers' waiting times are determined by service headways. Variations in service headways imply longer passenger waiting times and increased on-board discomfort as fewer passengers experience the short headways and more passengers experience the long headways (Cats, 2014). This results in an under-utilization of service frequency and capacity. Notwithstanding, at the time of writing the contract between the Ministry of Transport and the incumbent operator refers to schedule adherence upon departure from the terminal as the sole indicator of service reliability that impacts the incentive scheme.

Different measures can be used for quantifying headway variability (Trompet et al., 2011; Cats, 2014). The coefficient of variation of the headway offers a robust statistical measure proposed in the Transit Capacity and Quality of Service Manual (TCRP, 2017) is calculated as follows:

$$CV(h) = \frac{\sigma_{h_{k,s}}}{\sum_{k\in K}\sum_{s\in S} h_{k,s}/(|K|\bullet|S|)} \tag{1}$$

where each headway observation, $h_{k,s}$, corresponds to the actual headway between trip $k \in K$ and the successive trip at stop $s \in S$, where K is the set of vehicle trips traversing a specific line under a certain period, S is the set of stops on the respective line and h_p is the corresponding planned headway. $\sigma_{h_{k,s}}$ is the standard deviation of the observed headways. Note that the waiting time is in this calculation independent of the planned service headway, h^p. For fixed-route high-frequency bus services, the level of service (LoS) can be classified according to the coefficient of variation of headways (see Table 2).

Fig. 2 presents the evolution of the coefficient of variation of headway, $CV(h)$, along each line direction for the morning peak period (6–9). Line lengths were scaled to display all line directions in the same plot and allow for their direct comparison. In addition, the corresponding LoS is indicated. The LoS of all lines does not meet the requirement of the Israeli guidelines for planning and operating public transportation on buses. The guidelines specify a LoS C

Table 2
The level of service classified based on the coefficient of variation of the headway.

Level of Service	CV(h)	$p(\lvert h_{k,s} - h^p\rvert > 0.5h^p)$	Passenger and operator perspective
A	0.00–0.21	≤ 2%	Service provided like clockwork
B	0.22–0.30	≤ 10%	Vehicles slightly off headway
C	0.31–0.39	≤ 20%	Vehicles often off headway
D	0.40–0.52	≤ 33%	Irregular headways, with some bunching
E	0.53–0.74	≤ 50%	Frequent bunching
F	≥0.75	>50%	Most vehicles bunched

Source: Transit Capacity & Quality of Service Manual, 3rd Edition.

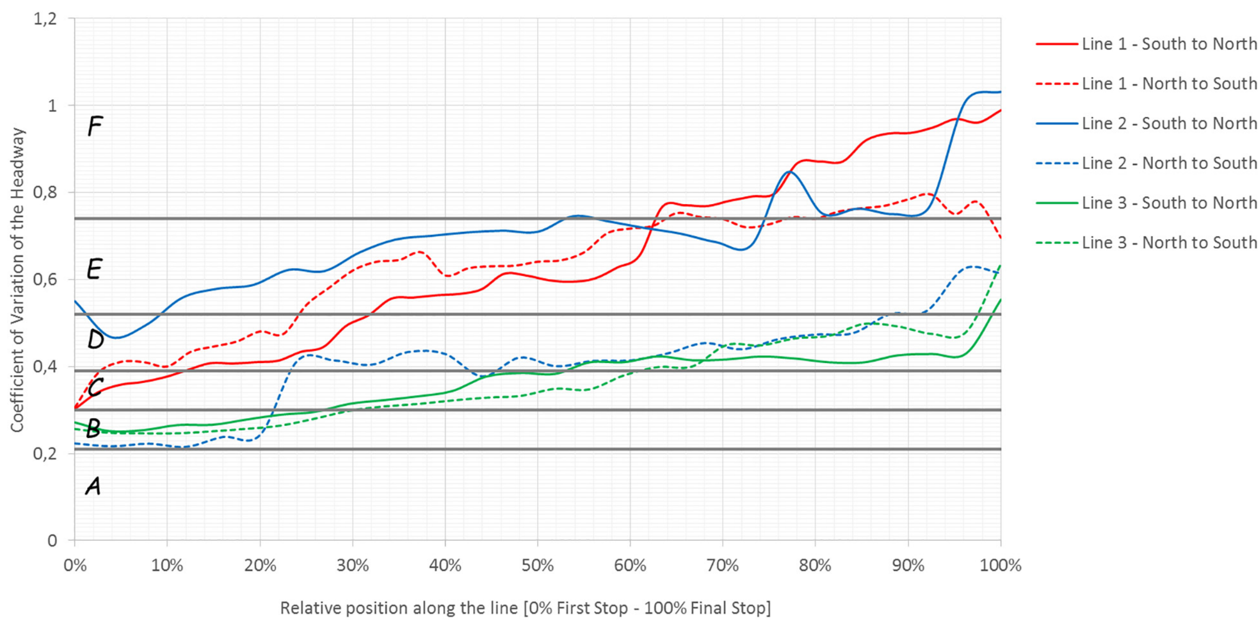

Fig. 2. The coefficient of variation of headway for each line-direction.

($0.31 < CV(h) < 0.39$) for BRT lines at each stop (i.e. along the entire route). In the case of both directions of Line 1, vehicles dispatch from the terminal at a LoS C which is maintained only for few stops after which headway variability deteriorates dramatically with the majority of the stops experiencing LoS E or F. The northbound direction of Line 2 dispatches with very uneven headways and fails to attain a LoS C at any of the stops along its route. In contrast, the southbound direction of Line 2 as well as both directions of Line 3 attain a LoS B or C for 25–60% of the route, after which the LoS deteriorates to D and even E towards the end of the route.

Despite the high-frequency BRT services, the procurement agreement between the public transport authority in the Ministry of Transport and the incumbent operator implies that the latter is required to apply a schedule-based rather than a headway-based control strategy. Each BRT vehicle is equipped with a computer screen that is situated in the driver cabin and is designed to inform the driver regarding the vehicle position in relation to the timetable. To ease the communication and reduce the information load for drivers, performance is displayed and updated using a colour scheme: Green – on schedule, Red – ahead of schedule, Yellow – behind schedule. This enables drivers to respond en-route in real-time to deviations from the schedule by holding at stops or adjusting their speed between stops. Buses are considered to be on-time as long as they are within the [−2 min, +2 min] time window in relation to the timetable. Drivers are instructed to adjust their speed and dwell times at stop as much as possible in order to attain on-time performance. In addition, dispatchers situated in the control centre monitor the BRT vehicles at the network-level and can intervene in the operations in case needed.

As evident in Fig. 2, headways between successive vehicle dispatching from the terminal exhibits large variations. This results with a LoS ranging between B and E already at the first stop after which service variability tends to propagate as a result of the well-known bunching effect caused by the positive feedback loop between service headways, number of boarding passengers and dwell times at stops. This ‘snowball effect’ is illustrated in Fig. 3 which presents an example of vehicle trajectories using a time–space diagram. It can be observed that buses tend to gradually get bunched, resulting with pairs of buses followed by long intervals. Bunching is particularly visible after stop 26 which is characterized by large passenger volumes and after which in one instance four buses are platooned together.

4. Travel time and fleet management

Service reliability is not only a key determinant of passenger level of service, but also an important factor influencing vehicle travel time variability and consequently fleet size requirements. The latter is determined by the average as well as variability of vehicle trip times.

Before the BRT went into operations, travel times had to be estimated in order to determine the fleet size. With the help of a microscopic transit simulation model, the total travel times for the three lines were estimated as follow:

- Line 1, 55 min, a commercial speed of 28 km/h
- Line 2, 45 min, a commercial speed of 24 km/h
- Line 3, 45 min, a commercial speed of 21 km/h

The all day average total travel times are 60 min, 49 min and 47 min for Lines 1,2 and 3, respectively. These vehicle trip travel times are 4 to 9% longer than has been expected based on the microsimulation transit assignment results, respectively. This discrepancy is attributed to the naïve assumption in the microsimulation that buses dispatch from terminals with even headways, in contrast to the observed large variations. This resulted with a severe underestimation of the severe bunching that occurs along this line, as discussed in the previous section. Given the segregated right of way, buses have very limited or no possibility to overtake each other over long stretches of the route.

Fig. 4 presents the average and standard deviation (indicated with black bars) of the commercial speed for each line direction and time periods. It is evident that higher commercial speeds in the range of 24–26 km per hour are attained on line 1 than on other lines. Moreover, speeds are consistently high on all trips of Line 1 resulting with a low standard deviation while lines 2 and 3, and in particular the southbound direction of Line 2, are subject to speed variations. The higher speed and the lower variability in speed for Line 1 stems from the impact of a full and unconditional traffic signal priority given at all signals along its route. Prior to its implementation, the total travel time of line 1 used to be 71 min on average, and a standard deviation approaching 9 min (compared with 60 and 3.4 min, respectively, following its implementation). Hence, the total vehicle trip time reduction attributed to traffic signal priority is at least 18% and contributed to a 60% reduction in the standard deviation of trip time. As part of ongoing developments, traffic signal priority is currently gradually

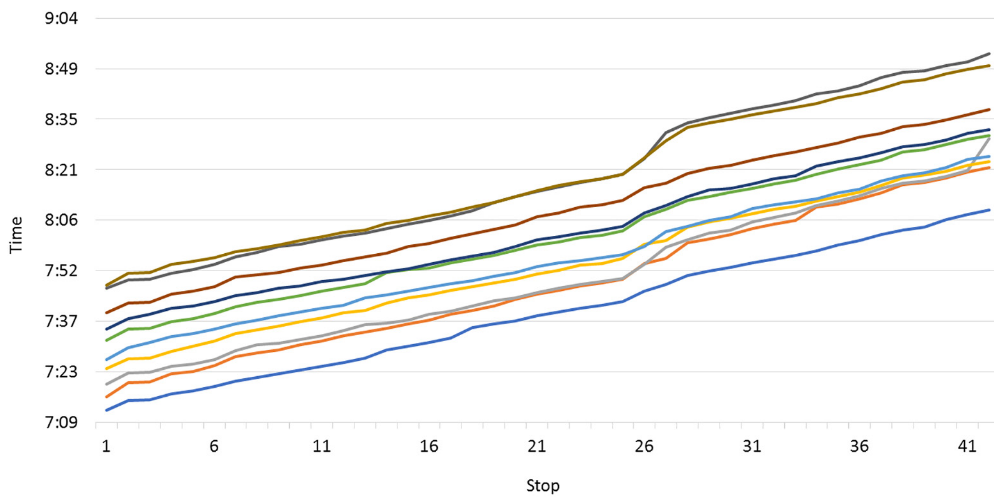

Fig. 3. Example of bunching occurrence among Line 1 (southbound, morning peak period).

introduced along the routes of Lines 2 and 3. As can be expected, speeds are higher in the evening period.

The total travel time and the travel time variability affect the fleet size requirements. The fleet size is determined so that vehicle availability is guaranteed at the 99% level. The corresponding percentile of the cycle time is calculated by summing the total travel time in each direction, adding three times the standard deviation, plus the driver break (i.e. 10 min per cycle). This value is then divided by the interval between trips (i.e. headways) to obtain the minimum fleet size requirement. In the case of Line 1 for instance, the current standard deviation of travel time results with four more buses than would have been required if the service exercised no variations. Hence, reductions in travel time variability, not only average travel time, can have significant implications for the operational costs.

5. Service utilization and crowdedness

Ticket validation and automated passenger counts data allow inferring passenger load profile along each of the BRT lines. Fig. 5 shows the average number of boarding passengers per vehicle trip during each time period and averaged over the whole day. It can be observed that both directions of Line 1 are not only the most heavily-utilized services (Table 1) but also most saturated when considering the provisioned supply, with 119–120 passengers per vehicle trip. Line 3 and Line 2 have on average 95–99 and 62–75 boarding passengers per vehicle departure, respectively.

There are noticeable differences between line directions in the different time of the day periods, indicating a clear directness in travel demand. In the morning peak period (6–9), the southbound direction carries more passengers as most travelers are heading from the suburbs in the municipalities stretching along the northern part of the Haifa Bay to downtown Haifa. The opposite pattern is observed in the afternoon peak period (16–19). Interestingly, passenger volumes are very high, and on some line directions the highest, in the periods traditionally considered to be off-peak, before and after midday (9–12 and 12–16). This indicates that the lower service headway offered during these periods (Table 1) result in larger volumes per bus and may need to be reconsidered to better dimension service supply to the observed demand. We further investigate passengers' trip durations along the day for each line. With few minor exceptions the average on-board travel time per passenger hovers between 8 and 12 min for all line directions and all hours of the day.

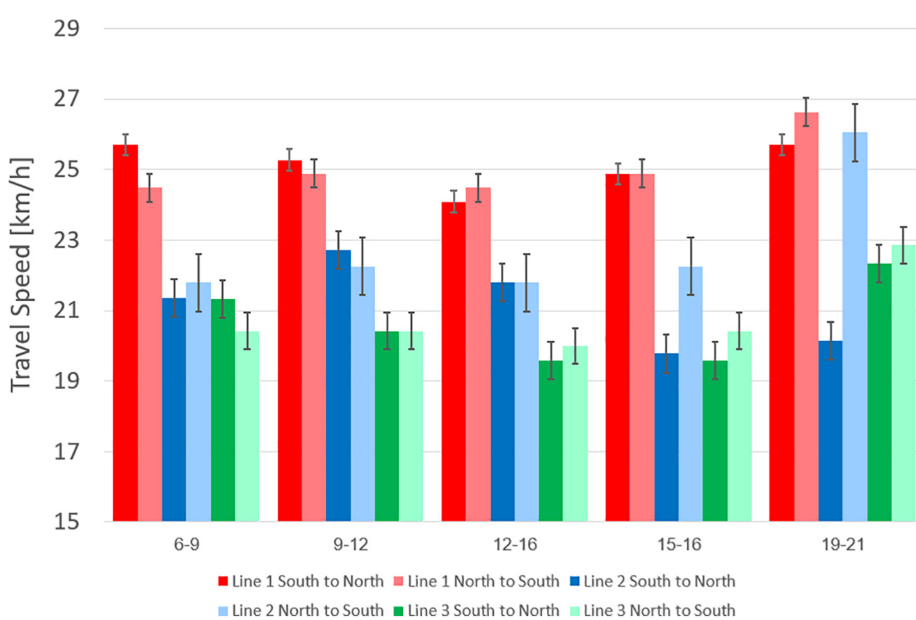

Fig. 4. Commercial speed per line-direction and time period.

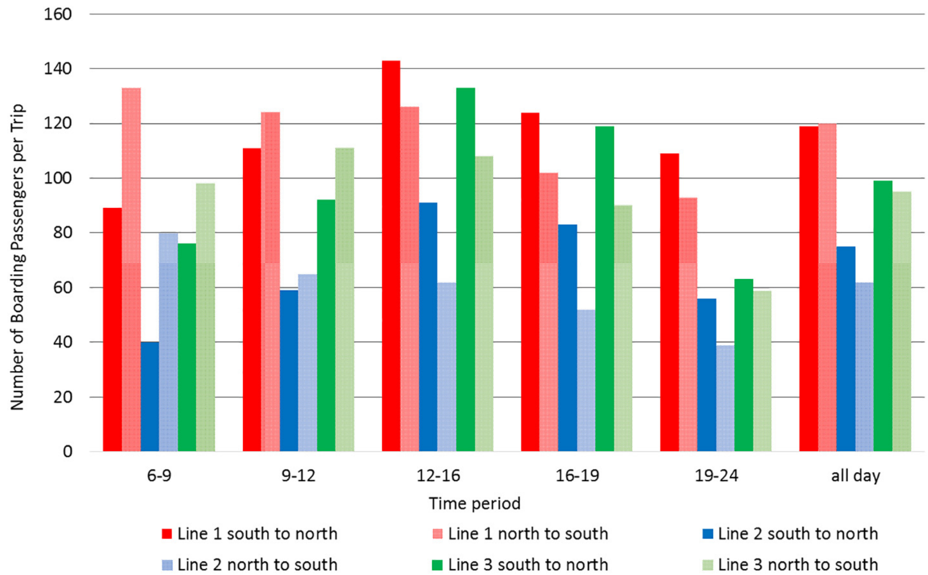

Fig. 5. Number of passengers boarding per trip.

The average number of boarding passengers may not be indicative of the crowdedness experienced by passengers for several reasons: (i) crowding levels vary significantly along each route; (ii) even within the same time period, there are significant variations among trips of the same line, exacerbated by bunching; (iii) more passengers experience the more crowded situations.

The average on-board occupancy along line 1 is depicted in Fig. 6 for both route directions for the respective peak hour – morning for the southbound direction and afternoon for the northbound direction. The southbound direction is on average more crowded (see Fig. 5) and also reaches high saturation levels on average during the morning peak. The busiest section is clearly the axis connecting the port of Haifa and the commercial and light industry areas on the eastern shore of the bay. The same axis is also the busiest section in the northbound direction, albeit high lower utilization levels on average.

Even for a given line direction, hour and route segment, the average value may not adequately represent passenger experience of the on-board crowding conditions. On-board occupancies exhibit pronounced variations even within the peak hour period as illustrated in Fig. 7 for a representative weekday (May 14, 2017). Moreover, these variations are clearly co-related to the headway from the preceding bus. While the planned headway is 4 min, the headways vary between 1 and 10 min during the analysis period. Bus trips with long front headways are overcrowded while buses with short headways are underutilized. This is a manifestation of the bunching phenomenon resulting from the positive feedback loop between service headways, passenger volumes and dwell times. As can be seen in Fig. 7, the seats capacity is exceeded during a substantial share of the route for most bus trips in the peak hour. Moreover, for the busiest section of the line (approximately stops 6–16, see also Fig. 6, left) the on-board occupancy surpasses the design capacity. A further investigation reveals that every fourth bus trip operating on line 1 in the morning peak period experiences crowded conditions on part of the route (24%, > 80 passengers on-board), while 7% exhibit extremely crowded situations (> 100 passengers) and 1% highly severe conditions (> 120 passengers).

6. Travel satisfaction

As part of the contract between the Ministry of Transport and Dan North (the operator), travellers' satisfaction is monitored on a regular basis, assess the level of service and determine whether the operator adheres to the requirements. In the survey, respondents are asked to indicate their satisfaction with 14 service attributes of the BRT system as well as their overall satisfaction with the service as a whole. The satisfaction scores range between 1 (very dissatisfied) to 5 (very satisfied).

Fig. 8 presents the average satisfaction scores from the latest survey. A sample of 5010 passengers participated in the on-board survey which took place on March 2017. The average overall satisfaction with the Matronit is 3.82 out of 5. Unfortunately, no satisfaction survey data is

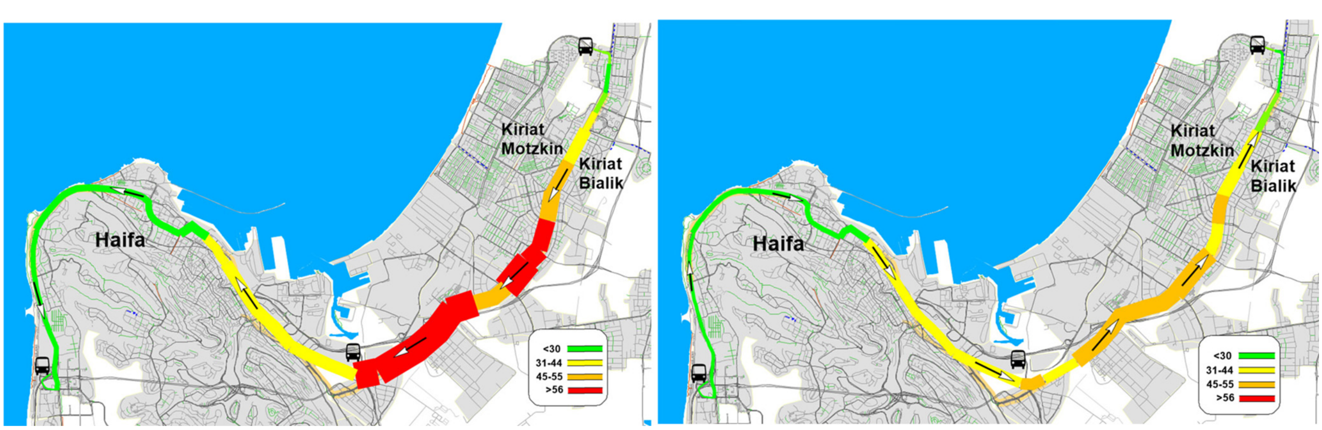

Fig. 6. Average on-board occupancy along BRT line 1 during weekday peak hours: southbound on 7–8 AM (left) and northbound on 4–5 PM (right).

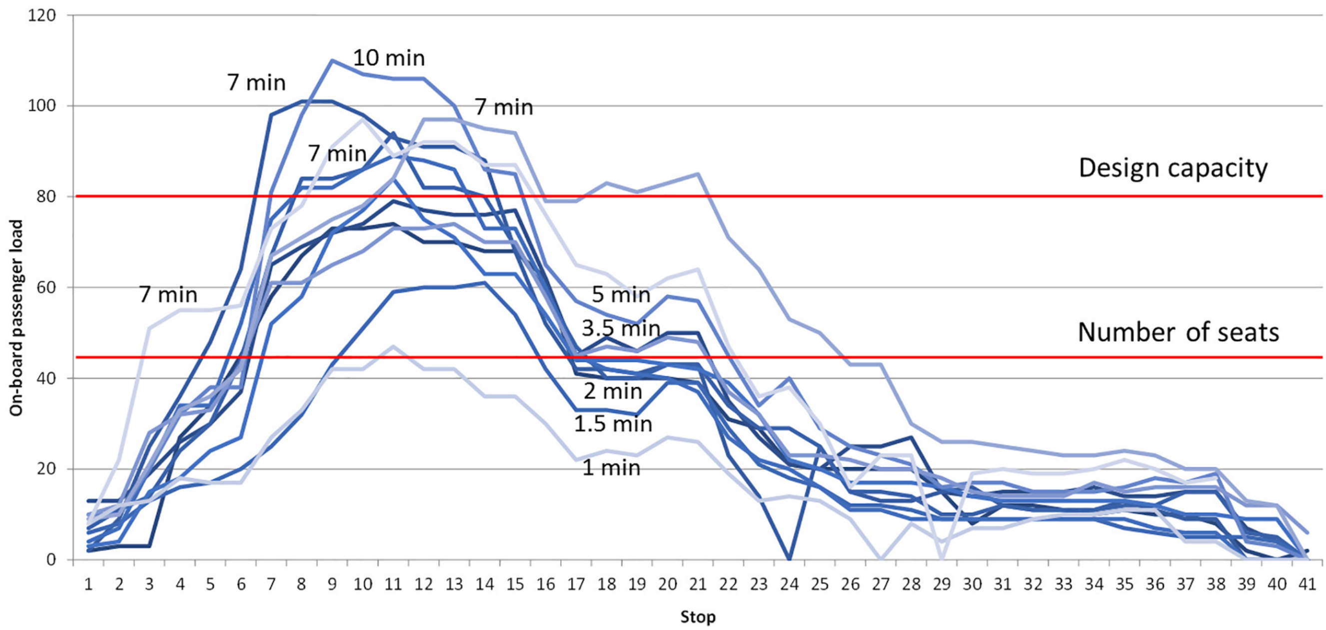

Fig. 7. On-board occupancy on trips running on the southbound BRT line 1 during the morning peak hour (7–8 AM) of a selected weekday. Darker lines correspond to later departures and the headway from the previous bus is displayed for each trip.

available for other bus services to allow for benchmarking. The Matronit is rated particularly high on driver adherence to traffic rules (4.17), driver appearance (4.15) and punctuality (3.96). In contrast, the lowest scores are given to crowding (3.10), ease of tickets purchase (3.26) and ticket validation at stop (3.36). The latter two can be attributed to difficulties that some users, in particular among the elderly and low socio-economic levels, experience in using technological means. Similarly, the replacement of on-board ticket sales with smart-card validation and mobile phone ticket purchase in Sweden led to a significant deterioration in the satisfaction with ticket accessibility (Cats et al., 2015). We further examine the satisfaction results per line and found that riders of line 2 are overall most satisfied with the BRT system as a whole as well as with most individual service attributes including service reliability and the reliability of real-time information while riders of line 3 are least satisfied with service frequency. Passenger satisfaction evaluations overall aligns thus with the measured service performance reported in the previous sections.

In addition, the passengers were asked to answer the question: “Which travel mode would you choose if there was no Matronit”. In response to this what-if question, 67% of the respondents indicated that they would have travelled by bus, 11% by car as drivers, 8% would have used taxi, 6% walk, 5% car as passenger, 2% will cancel their trip and 1% resort to other modes. The results indicate that for 16% of the Matronit users it serves as a substitute for car, two thirds of which as a driver.

7. Discussion and conclusion

The design of BRT systems around the world is geared towards providing a high-capacity fast, reliable and comfortable public transport service. Previous studies provide extensive insights into the high-level design principles and ridership impacts of BRT systems. The case study analysis conducted in this study sheds light on tactical and operational aspects of planning and managing BRT systems and services

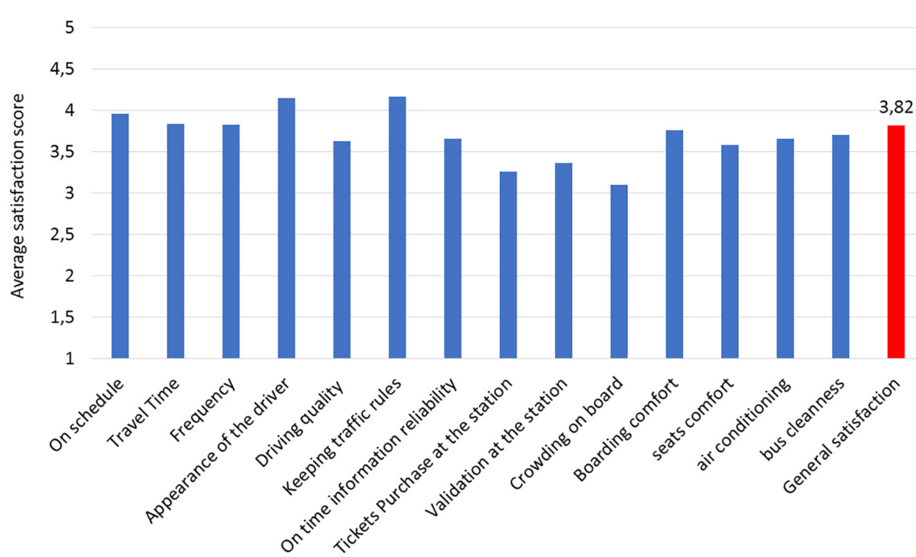

Fig. 8. Satisfaction characteristic scores.

that strive towards BHLS. While these aspects are detrimental for realizing the potential speed, reliability and comfort of such systems and their strategic and infrastructure investments, there is limited empirical knowledge on how performance varies across systems and related underlying reasons. In this study, we examine the operational performance of a new BRT system, the Matronit in Haifa, the first of its kind in Israel, using detailed empirical data.

While the introduction of the BRT system has significantly upgraded service provision in comparison to the previous conventional bus service in several key aspects, it has not yet achieved the target level of service reliability set by the Ministry of Transport. The busiest line directions fail to attain the desired level of service C, characterizes as vehicles being often off the planned headway, for the vast majority of their operations, deteriorating instead to levels of service E and F. This snowball effect starts with high headway variations already upon dispatching from the terminal and then exacerbates along the line. The key factors contributing to the current level of service are the irregular dispatching from terminals and the absence of a regularity-driven mode of operations along the route. This calls for the introduction of a real-time control strategy suitable for high frequency service as well as the further deployment to traffic signal priority measures.

. Evidently, the current schedule-based dispatching regime does not yield a regular service. Results from field experiments in Stockholm demonstrate that a headway-based control strategy can mitigate bunching along the line, especially when vehicle scheduling allows for headway-based dispatching (Cats, 2014). Improvements in service reliability will directly lead to reduced passenger waiting times as well as a more even distribution of passenger loads, hence resulting in improved on-board crowding and more efficient capacity utilization. The latter is expected to elevate passenger satisfaction with on-board crowding, which is currently the service attribute that passengers are least satisfied with. Further research should fuse on-board survey data with passively collected data to allow for directly linking experienced service performance to reported travel satisfaction level at the individual level.

Next to passenger experience, improvements in service reliability have also consequences for fleet management. The average commercial speed ranges for the most part between 20 and 25 km per hour for the different line directions, but the variation of which results with the necessity to allocate up to four extra buses. The deployment of traffic signal priority has shown to contribute significantly to a reduction in the average as well as variation of vehicle trip times. A more regular service is expected to yield additional gains in operational efficiency.

In the analysis presented in this study, we investigated the performance of the BRT network while analysing each line in isolation. Network performance may however depend also on the interaction between lines especially in cases where (i) a considerable share of the passengers transfer from one line to another or (ii) that some of the lines run along a common corridor and a considerable share of the passengers travel within this corridor. From a network design perspective, offering several BRT line that partially run in shared corridor can not only offer a high joint frequency along the trunk but also reduce the need to transfer for those heading to one of the branches, albeit introducing additional complexity for example in relation to inter-line headways, especially when merging. Notwithstanding, recent developments allow for integrating single-line performance with corridor management and transfer synchronization considerations when making real-time control decisions (Gavriilidou and Cats, 2018; Laskaris et al., 2019).

Our experience with the Matronit points to the importance of closely examining and removing barriers to service performance through short lines of communication among key stakeholders. It is therefore advisable to form a performance analytics working group which in addition to the service operator comprises of professionals at the operational management level from the tendering authority, the local transport authority and the local traffic control centre. Regular meetings will facilitate monitoring progress, identifying bottlenecks and opportunities for improvements for instance in relation to station layout, traffic signal programs and information campaigns.

Further research into benchmarking BRT and BHLS systems in terms of service regularly, fleet management efficiency, service utilization and customer satisfaction will allow planners and operators to assess their performance not only in relation to past performance but also compared with peer-systems around the world.

Declaration of Competing Interest

There is no conflict of interest.

Acknowledgment

The data for this work were provided by Yefe Nof, Transportation, Infrastructure Constructions LTD.

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