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RESEARCH

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A simulation-based evaluation of BRT systems in over-crowded travel corridors: a case study of Cairo, Egypt

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Abstract

This paper examines the performance of bus rapid transit (BRT) systems in over-crowded travel corridors. A case study of King Faisal Street in Greater Cairo Region GCR, Egypt, was adopted. A simulation model was developed using PTV VISSIM simulation platform for the study area. A data collection effort was exerted to collect operational traffic data required for model development/calibration. As BRT systems share the roadway with other modes of travel (vehicles, pedestrians, etc.), handling conflicts is a major challenge that faces operations, especially in over-crowded travel corridors. Four BRT scenarios were developed with different conflict treatment methodologies (vehicle/BRT conflicts at U-turns and vehicle/passenger conflicts near BRT stations), varying from signal control at each BRT station (scenario 1) to complete grade separation (scenario 4). Each of the developed scenarios was thoroughly assessed based on disaggregated segment travel times, aggregated corridor travel times, capacity to accommodate travel demand, and corridor level of service. A wide range of results was reported for the impact of the proposed systems on corridor traffic operations varying from 80% increase in overall travel time (scenario 1) to 18% reduction (scenario 4). Such results highlight the potential of BRT systems in improving traffic operations in over-crowded traffic corridors and the vital role of conflict treatments in achieving successful operations.

Keywords: Bus rapid transit, Exclusive bus lane, Over-crowded corridors traffic conflict treatment

Introduction

Greater Cairo Region (GCR) is a vivid example of an over-crowded megacity, of 1709 km^2 in area and more than 23 million inhabitants. GCR has a dense roadway network with over 36,000 km of paved roads, serving over 20 million daily motorized person trips [1]. A study sponsored by the World Bank [2] estimated an annual monetary cost of traffic congestion in GCR in 2010 of about 47 billion LE (8 billion USD), resulting in a per capita cost of around 2400 LE (400 USD). Such cost is estimated to be around 15% of the total per capita GDP. About 65% of this cost is a direct cost, with delay representing the largest proportion of the direct cost (around 31%). Such figures reveal the imminent need for policies and measures to reduce traffic delays on a network-level scale.

Increasing the rider share of public transport has always been considered as a viable option for alleviating traffic congestion. Bus rapid transit (BRT) systems attempt to enhance public transport capacity/level-of-service in a cost-effective fashion. Dedicated bus lanes, high frequency, and operational priority are the main characteristics of a BRT system. The BRT standard [3] defines a BRT system as "a section of a road or contiguous roads served by a bus route or multiple bus routes that have dedicated lanes with a minimum length of 4 km,"

BRT systems have several successful implementations in China and South America. The BRT Standard latest edition has produced a list of rated BRT corridors meeting the minimum definition of BRT in China, Colombia, Brazil, Pure, Mexico, Guatemala, and Tanzania [4]. The attributes used to evaluate BRT performance include (1) vehicle headway (busses can operate at headways of 10 s or less), (2) vehicle capacity (the capacity of BRT vehicles can range from 50 passengers for conventional busses and up to 250 for articulated vehicles with standing passengers), (3) the effectiveness of the stations to handle passenger demand, (4) the effectiveness of the feeder system to deliver passengers to stations at the required speed, and (5) local demand.

BRT systems attempt to alleviate traffic congestion by maximizing per lane passengers' throughput. Based on BRT standards, BRT lane throughput could reach up to 90,000 passengers per hour per direction (PPHPD) (250 passengers per vehicle, one vehicle every 10 seconds). In the real world, TransMilenio holds the record, with 35,000–40,000 PPHPD with most other busy systems operating in the 15,000 to 25,000 PPHPD range.

As BRT systems share the roadway with other modes of travel (vehicles, pedestrians, etc.), handling conflicts is a major challenge that faces operations, especially in overcrowded travel corridors (where travel demand exceeds the corridor operational capacity) and given tight budget constraints. Such a challenge mandates examining different conflict treatment scenarios to ensure system efficiency/effectivity while minimizing cost. As such, this paper examines the different conflict resolution strategies for a proposed BRT system on one of the city's busiest travel corridors, Faisal Street. The conducted analysis is intended to shed the light on the appropriateness of different conflict resolution strategies and their impacts on system performance.

Case study corridor

Faisal Street, in Giza, Egypt, is a vital 6-lane divided 7 km arterial that carries significant daily traffic volumes with an average peak period running speed of 15 km/h. The modal split on Faisal Street is mostly dominated by passenger cars/taxis (around 65%), followed by microbusses (around 25%). Faisal Street runs parallel to another major arterial, Haram Street, both providing access to Giza pyramids, Cairo/Alexandria Dessert Road, and Cairo/Fayoum Desert Road (Fig. 1). Faisal Street suffers from daily congestions caused by excessive commercial and residential activities, lack of adequate public transport, busses, poor/random service of microbusses, lack of parking spaces that often lead to illegal parking rows, and high pedestrian densities on travel lanes. The poor service of microbusses and the random stops cause an excessive reduction in the corridor capacity [5].

Several side streets connect Faisal/Haram streets with the rest of the network, forty-three of which were considered, as shown in Fig. 2. All intersections are right-in/

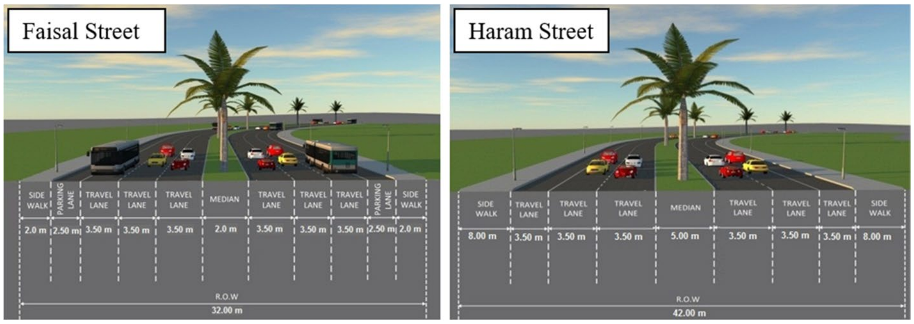

Fig. 1 Faisal and Haram Streets cross-sections

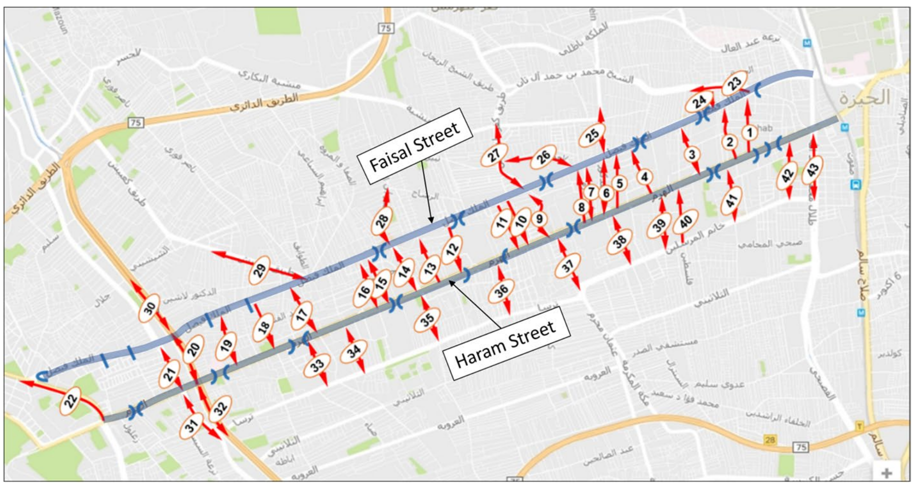

Fig. 2 Side streets and existing U-turns on Faisal and Haram Streets

right-out; only right turn movements are permitted. Left/through movements are, alternatively, handled through downstream U-turns.

Traffic data was collected along Faisal Street, Haram Street, and several side streets. Data was primarily consolidated from previous studies [2, 6–13]. In addition, field observations were conducted. Observed PM peak hour traffic volumes reached 4400 vph, with more than 60% coming from the east end of the street (from Faisal bridge). For more details, see Mohamed M. [1].

U-turn movements along Faisal and Haram Streets are of vital importance, specifically for their potential conflicts with the BRT route. Field observations have been conducted to record the turning movement percentages. Observed tuning percentages ranged from 2 to 25% of the total through volumes.

Simulation model development and calibration

A replica of the case study roadway network geometry has been created in the PTV-VISSIM simulation environment. Collected traffic volumes and turning movement percentages have been added to replicate traffic conditions. A calibration exercise was adopted to ensure model realism. The calibration exercise was conducted in two steps:

1. Capacity calibration: field data was collected to estimate the actual capacity of the road. Related parameters have been manipulated to replicate field observations (mean following headway, critical gap for lane change, driver reaction time, and the queue discharge headway).
2. System performance calibration: parameters were adjusted to minimize the difference between observed and modeled travel speeds/times. The corridor is divided into segments each of 1 km to enable proper comparison of performance measures.

A statistical test (K-S test) was consulted to verify the model adequacy, based on the difference between observed and modeled travel speeds [14–16]. Prior to the calibration exercise, the maximum difference $D_{m,n}$ was 0.97, compared to a critical value of $D_{m,n,\alpha}$ of 0.06. After calibration, the difference was reduced to 0.05. Additionally, the mean absolute percent error (MAPE), root relative square error (RRSE), and normalized root mean square error (RMSEN) were estimated to further evaluate the model adequacy based on travel time accuracy. The calibrated model returned a MAPE of 6%, RRSE of 10%, and RMSN of 12%. The reported results were deemed acceptable as per the FHWA Guide [17], which indicated a threshold error of 15%.

BRT system layout

BRT alignment

The proposed BRT on Faisal Street takes one lane from the median edge to be exclusive for busses. Figure 3 depicts the proposed BRT alignment and proposed modifications to the street cross-section. The bus route starts under Faisal Bridge and continues on an exclusive route, parallel to the exit ramp of Faisal Bridge. BRT route switches to the median lane, till the end of Faisal Street. In the opposite direction; the BRT route occupies the median lane and switches to the edge lane (right lane) before the entry ramp of Faisal Bridge.

To complement the proposed alignment and to accommodate parking needs, a proposal was put forward to utilize two areas within the study area boundaries for constructing two multi-story parking facilities: at the beginning and end of Faisal Street. The proposed facilities would accommodate parking demand, specifically, after prohibiting parallel parking on both sides of Faisal Street. In addition, such a facility would help encourage people to park their private vehicles and use BRT.

BRT stations

Faisal Street witnesses several retail/residential activities on both sides, which requires multiple BRT stations. The locations of BRT stations were chosen based on areas of high demand. The distance between stations is between 300 and 800 m, as per the Transit Capacity and Quality of Service Manual (TCQSM) [18]. Figure 4 shows the locations of proposed BRT stations, each point represents two waiting stations (one station per direction). The location of some of the U-turns along Faisal Street has been slightly

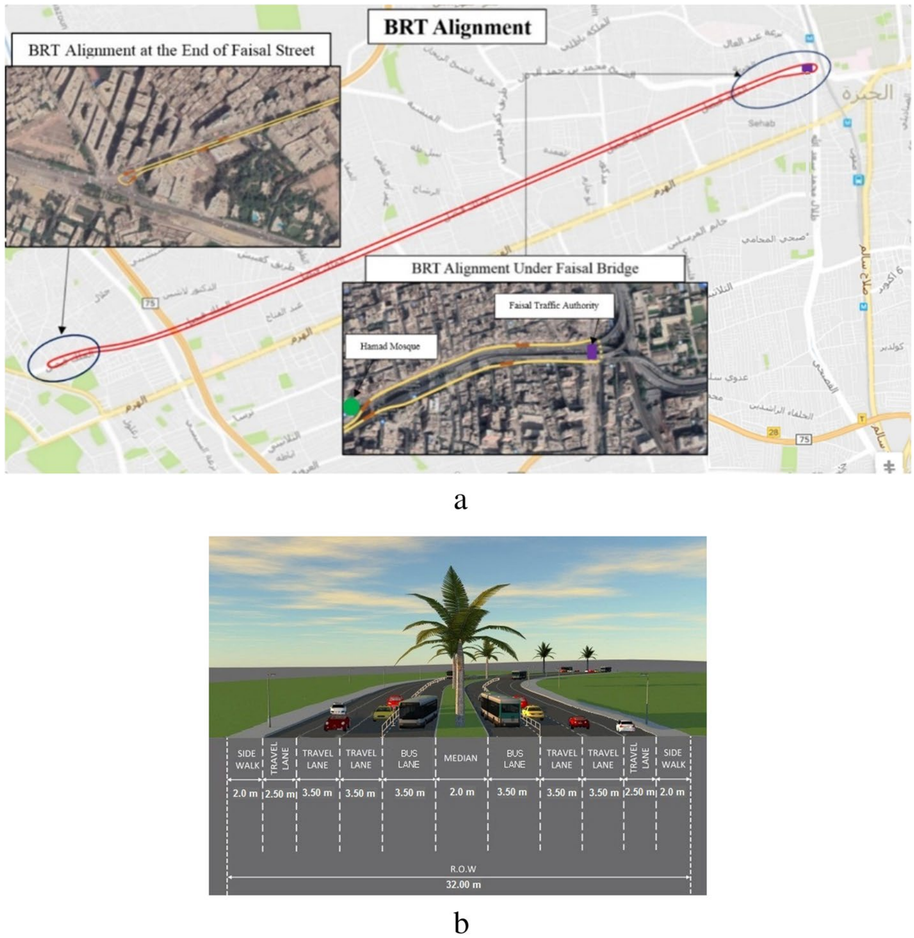

Fig. 3. Proposed BRT system configuration. **a** Proposed BRT alignment. **b** Proposed cross-section for Faisal Street

modified according to the stations' locations. All U-turns were located immediately downstream of the closest BRT station.

BRT operations and conflict resolution scenarios

An articulated bus is chosen to serve the proposed BRT system with a frequency of 60 busses/h. The selection is based on the expected high volume of passengers and the need for high capacity for the BRT system. In over-crowded traffic corridors, the impact of conflicts between vehicles on traffic lanes and BRT bus/passengers is magnified. Two conflicts are of concern: vehicle/BRT conflicts at U-turns and vehicle/passenger conflicts at BRT stations. Vehicles making U-turns need to cross the BRT lane, causing vehicle/BRT conflict. Passengers accessing the BRT station need to cross the traffic lanes, causing vehicle/passenger conflict.

Four BRT design scenarios were developed with different approaches for handling conflicts (vehicle/BRT and vehicle/passenger conflicts). Resolution methods vary from speed bumps to grade separation. In scenario 1, U-turn movements are allowed

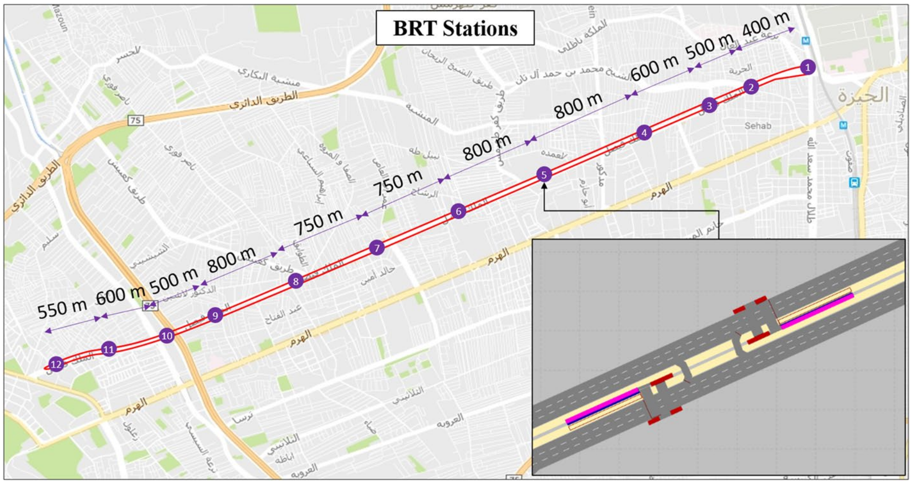

Fig. 4 Locations of the BRT stations

downstream of each station. A traffic signal is to be installed at the front end of each BRT station to handle vehicle/BRT conflicts as well as vehicle/passenger ones. Vehicles are allowed to make U-turns through a dedicated left-turn signal phase. Passengers are allowed to cross traffic lanes through a pedestrian signal phase. The number of permitted U-turns is reduced in scenario 2 and, hence, reduced locations of vehicle/BRT conflicts and reduced number of traffic signals. Nonetheless, in stations with no U-turns, crossing of passengers is treated by either speed bumps or pedestrian signals, based on expected crossing intensity.

A further reduction in the number of permitted U-turns is implemented in scenarios 3 and 4. Grade separation is proposed to handle vehicle/BRT conflicts at U-turns through a BRT bridge, in both scenarios. The bridge separates the BRT lane from traffic lanes in the vicinity of U-turn locations. However, scenarios 3 and 4 differ in the way they handle vehicle/passenger conflicts, as presented in Table 1. Figure 5 presents the spatial distribution of the proposed conflict resolution methods. While proposed scenarios vary significantly in their costs, performance evaluation is mandatory to guide the design process.

BRT simulation

A simulation-based assessment is undertaken to evaluate the corridor performance, given different conflict resolution methods. Enhanced network performance is expected to be observed from one scenario to the next, given the level of separation of movements. Nonetheless, the level of enhancement needs to be quantified to be able to assess cost versus expected benefits.

The developed simulation testbed was used to test the implementation of the proposed BRT design scenarios. Modifications in network geometry, controls, and traffic demands have been implemented based on design configurations. The change in demand was estimated based on BRT system capacity and modal shares along the corridor. Given the high demand for public transit in Faisal Street, the BRT system is assumed to operate in

Table 1 Conflict resolution methods

Scenario	Vehicle/BRT conflicts (at U-turns)	Vehicle/passengers conflicts (at BRT stations)
Scenario 1	At grade traffic signal	At grade traffic signal
Scenario 2	At grade traffic signal	At grade traffic signal, pedestrian only signal, and speed bump
Scenario 3	Grade separation BRT bridge	At grade pedestrian only signal and speed bump
Scenario 4	Grade separation BRT bridge	At grade pedestrian bridge and speed bump

full capacity. Different BRT capacities have been estimated for different scenarios based on their operational characteristics.

BRT passengers are assumed to be current commuters who use either private cars or existing public transit modes (mostly microbuses). The percentage of modal shift from microbusses to BRT is expected to be higher than that from private vehicles. As such, 75% of estimated BRT demand, for each scenario, is assumed to come from current public transit users (mostly microbus users), while 25% are new users (shifting from private vehicles). Full-size busses on Faisal Street are less than 3.8% and are mostly private transport; hence, they were not considered in the modal shift.

Several simulation runs (with a timeframe of 1 h) were performed to test the operational performance of each scenario. The average travel time for each 1 km on Faisal Street was estimated. In addition, traffic volumes entering the network within the simulation time frame (accommodated demand), average queue delay, and average speeds were recorded for each scenario.

Results

Travel times

Average travel times have been recorded for each kilometer of the corridor and benchmarked with current case values. Figure 6 displays the reported travel times for vehicles using the corridor and BRT busses (travel lanes and BRT lane travel times) along Faisal Street for all BRT scenarios in addition to the current case travel time.

Reduced travel times could be depicted from one scenario to the next for BRT lanes. However, different results have been reported for travel times on travel lanes. In the current case, Giza to Faisal direction, travel times tend to increase in the second half of the corridor due to the consolidation of traffic demand. Alternatively, in scenarios 1 and 2, there is an opposite trend where an increase in travel times is observed in the first half of the corridor. This variation in trend is a result of induced delays of proposed traffic signals which impeded the entry of vehicles from Faisal Bridge (main corridor feeder) to the network during the simulation hour and caused excessive delays. The percentage of the hourly traffic volume that was accommodated in the network from Faisal Bridge was around 65% of the estimated hourly demand. When vehicles reached the second half of the road, the traffic volume was significantly less than that of the current case resulting in an increased vehicle speed and reduced travel time.

In scenarios 3 and 4, with the absence of traffic signals, travel time variations followed the same trend of the current case. The observed pattern supports the idea that the

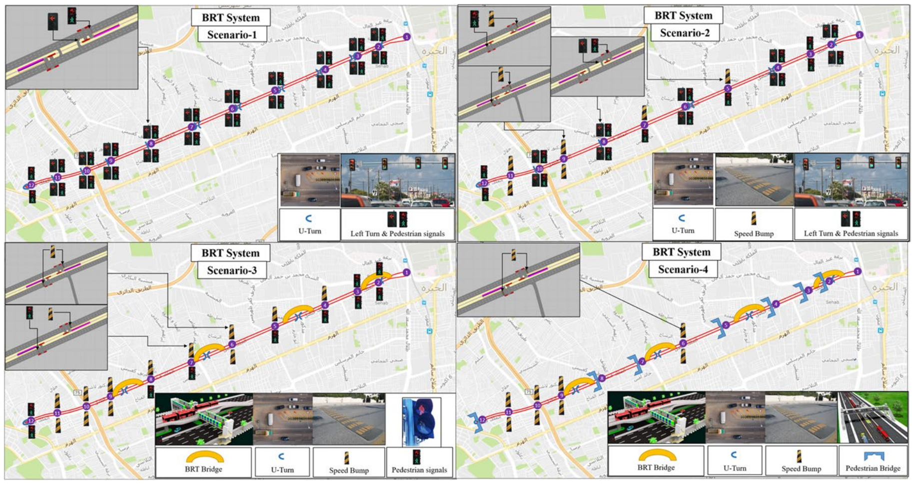

Fig. 5 Conflict resolution scenarios

presence of traffic signals in scenarios 1 and 2 is the main reason for the change in travel time pattern. Nonetheless, travel time (in scenario 3) in the first half of the road is still higher than that of the current case due to the presence of pedestrian signals causing considerable congestion.

In the other direction (from Faisal to Giza), travel time patterns were similar in all scenarios. Traffic volumes in this direction come from multiple entries from side streets with no major main line inflow causing large-scale bottlenecks. Nonetheless, the negative impact of traffic signals could be clearly depicted in the increase in travel lane travel times in all scenarios except for scenario 4.

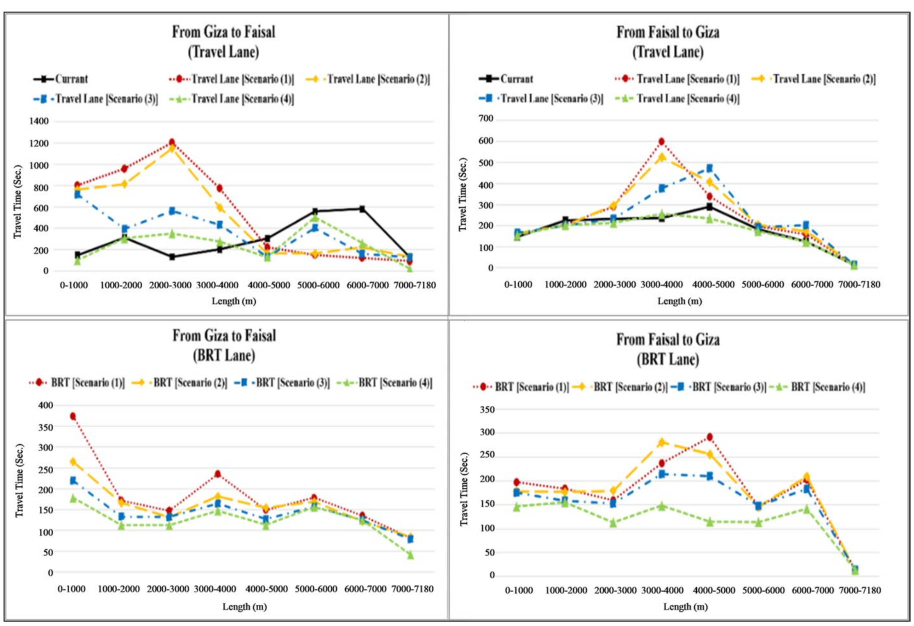

Fig. 6 Segment average travel time (travel lane and BRT lane)

Average corridor travel times have also been recorded to enable an overall comparison of network performance. Figure 7 and Table 2 show the comparison between total travel times for vehicles and the BRT system along both sides of Faisal Street. The impact of proposed BRT systems on vehicle traffic operations on travel lanes could be depicted, where it varies from an 80% increase in overall travel time (scenario 1) to an 18% reduction (scenario 4). However, in all proposed scenarios, the BRT System travel time is considerably less than that of vehicles using travel lanes.

Accommodated traffic volumes

The impact of the proposed BRT systems on traffic operations could be quantified by comparing the accommodated traffic volumes and original traffic demand. Figure 8 displays this comparison, for the direction Giza to Faisal. In scenarios 1 and 2, only 67% of the estimated traffic demand for Fasial Street was able to enter the network within a simulation timeframe of 1 h. In scenario 3, accommodated volumes are more close to the estimated demand on most access points, except for Faisal Bridge and El-Omda Street entries. The percentage of vehicles that were able to enter the network within the simulation time frame, in scenario 3, was 75% of the current case volume. Traffic/pedestrian signals played a critical role in impeding the entry of a significant portion of traffic demand to the network in the first part of Fasial Street. Alternatively, in scenario 4, enhanced traffic flow conditions were reported. The network was able to accommodate extra traffic volume of about 16% of the original demand.

Level of service evaluation

Table 3 summarizes the estimated level of service (LOS) for travel lanes and BRT lane for each scenario, based on TCQSM and Highway Capacity Manual (HCM), respectively [18, 19]. For travel lanes, a LOS (F) is estimated for the direction Giza-to-Faisal for the current case and scenarios 1 to 3. An enhancement is reported in scenario 4, where LOS improves from F to E in one direction and E to D in the other. The estimated LOS for the BRT lane is better than that of travel lanes in all scenarios. While LOS for travel lane did not exceed level E, BRT lane ranged from level E in scenario 1 to level B in scenario 4.

Conclusions

BRT has been successfully implemented as a cost-effective mass rapid transit system all around the world [4]. As BRT systems share the roadway with other modes of travel (vehicles, pedestrians, etc.), handling conflicts is a major challenge that faces operations,

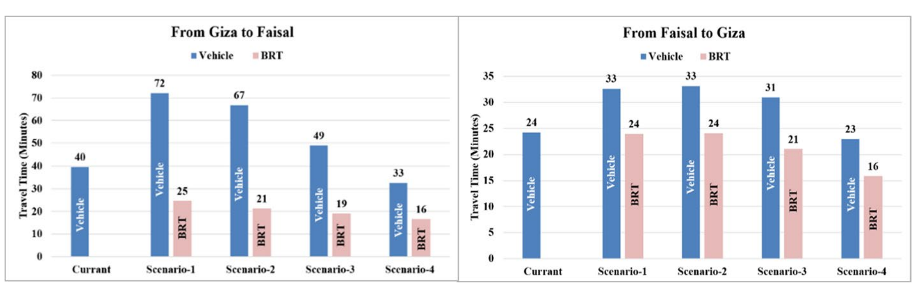

Fig. 7 Corridor average travel times for different operational scenarios

Table 2 Percent change in corridor travel times (travel lanes)

Direction	Change in average travel time			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
From Giza to Faisal	↑ 80%	↑ 67.5%	↑ 22.5%	↓ 18%
From Faisal to Giza	↑ 37.5%	↑ 37.5%	↑ 29.2%	↓ 5%

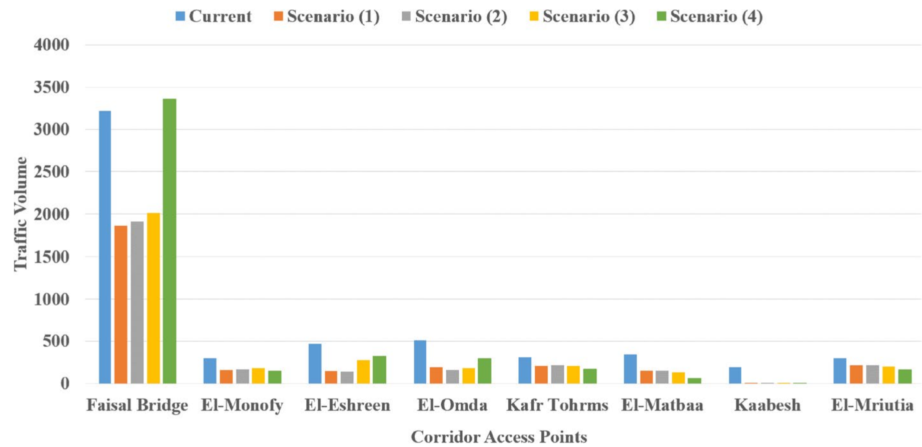

Fig. 8 Accommodated traffic volumes versus original traffic demands

Table 3 LOS evaluation of travel/BRT lanes for each scenario

	Direction	Current	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Travel lane	**From Giza to Faisal**	F	F	F	F	E
	From Faisal to Giza	E	E	E	E	D
BRT lane	**From Giza to Faisal**	–	E	E	C	B
	From Faisal to Giza	–	B	B	B	B

especially, in over-crowded travel corridors. This paper presents a simulation-based assessment of the performance of the BRT systems in over-crowded traffic corridors. A case study of an over-crowded traffic corridor in the Great Cairo Region, Egypt, has been adopted. A simulation model has been developed and calibrated to serve as a test bed for the evaluation of the proposed BRT performance and impacts. Different conflict resolution scenarios are examined. Two conflicts are of concern: vehicles/BRT conflicts at U-turns and vehicles/passengers conflicts at BRT stations.

Four BRT scenarios were developed with different approaches for handling conflicts. Scenario 1 uses traffic signals at the front end of all stations. In scenario 2, the number of U-turns is reduced, and consequently, the number of traffic signals is reduced as well. Pedestrian signals and speed bumps are used to enable the crossing of passengers. In scenarios 3 and 4, BRT bridges are used to resolve vehicles/BRT conflicts at U-turns. While pedestrian signals are used in scenario 3, pedestrian crossing bridges are used in scenario 4.

The simulation results reveal the significant adverse impacts of traffic/pedestrian signals in handling movement conflicts in over-crowded traffic corridors. The average corridor travel time increased for scenarios 1, 2, and 3 by 80%, 68%, and 23%, respectively, compared to the current case. Traffic/pedestrian signals also played a critical role in impeding the entry of a significant portion of traffic demand to the network in the first part of Fasial Street. A portion of the current case demand could not be accommodated during the simulation time frame in scenarios 1, 2, and 3. Scenario 4, on the other hand, accommodated extra demand of about 5% of the current case one. As for the estimated

LOS, an enhancement is reported only in scenario 4, where LOS improves from F to E in one direction and E to D in the other.

Based on the outputs of this study, grade separation is identified as the recommended conflict resolution approach for handling vehicles/BRT conflicts at U-turns/intersections and vehicle/passenger conflicts at BRT stations, in over-crowded travel corridors. The high toll associated with the interruption of vehicular flow using a traffic/pedestrian signal jeopardizes the overall benefits of adopting a BRT system. Excessive delays on traffic lanes are of eminent concern in this case.

Abbreviations
BRT: Bus Rapid Transit; GCR: Greater Cairo Region; PPHPD: Passengers per Hour per Direction; MAPE: Mean Absolute Percent Error; RRSE: Root Relative Square Error; RMSEN: Normalized Root Mean Square Error; TCQSM: Transit Capacity and Quality of Service Manual; HCM: Highway Capacity Manual; LOS: Level of Service.

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Authors' contributions
All the authors confirm contribution to the paper as follows: study conception and design—HT and NE; data collection and simulation model development—MM; analysis and interpretation of the results—MM, NE, and HT; draft manuscript preparation—MM, NE, and HT; manuscript review—HT. All authors reviewed the results and approved the final version of the manuscript.

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Availability of data and materials
All the materials, including and not limited to the descriptive analysis, tables, figures, statistical models, and equations, are included in the manuscript. In addition to that, all the relevant raw data, Excel sheets, data collected, and VISSIM files are freely available to any researchers who wish to use them for non-commercial purposes while preserving collected data's confidentiality and anonymity from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References
1. Mohamed M (2019) A simulation-based evaluation of BRT systems in over-crowded travel corridors. Master Thesis, Cairo University, Faculty of Engineering, Public Works Department
2. World Bank (2013) Cairo traffic congestion study. Phase 2, Ziad Nakat, Santiago Herrera and Yassine Cherkaoui.
3. The BRT Standard (2013) Institute for Transportation and Development Police Works (ITDP). http://www.itdp.org/microsites/the-brt-standard-2013
4. Institute for Transportation and Development Policy (ITDP) (2014) About the standard: what's new in 2014? 2013 Corridor Rankings
5. Abdelwahab H (2014) Stochastic macroscopic traffic simulation modeling for impacts of traffic chaos of microbuses. J Eng Appl Sci 61(1):25–42
6. Giza traffic authority (2016) Egyptian authority, traffic videos at Mashabek Station in Faisal Street for days (25/7/2016, 26/7/2016, and 27/7/2016)
7. Giza Governorate (2012) Traffic impact study of the construction of the supermarket Charisma Mart Project on Faisal Street
8. Giza Governorate Study (2012) The Macro Cash and Carry Company study to construct supermarket on Faisal Street
9. CREATS (Cairo Regional Area Transportation Study), Japan International Cooperation Agency (JICA) study (2002) Transportation master plan and feasibility study of urban transport projects in Greater Cairo Region in the Arab Republic of Egypt. Phase 1 Final Report, Volume 3: Transport Master Plan
10. Japan International Cooperation Agency - JICA SDMP (2008) The strategic urban development master plan study for sustainable development of the Greater Cairo Region in the Arab Republic of Egypt

11. World Bank (2010) Cairo traffic congestion study. Phase 1, ECORYS Nederland BV and SETS Lebanon.
12. PPP Cairo Study Report (2005) Code (NW10)
13. Transport and Traffic Unit at Ain Shams University, Egypt (2012) Traffic volumes on Haram Street
14. D'Agostino RB, Stephens MA (1986) Goodness-of-fit techniques. Marcel Dekker, Inc, New York
15. Kim, S. J., Kim, W., and Rilett, L. R. (2005) Calibration of micro-simulation models using nonparametric statistical techniques. Transportation Research Record, Journal of the Transportation Research Board, National Research Council, Washington, D. C., No. 1935, p 111-119
16. Real Statistics website, Explain two sample Kolmgorov-Smirnov test (K-S test). http://www.real-statistics.com/non-parametric-tests/goodness-of-fit-tests/two-sample-kolmogorov-smirnov-test/. Accessed Jan 2018
17. FHWA Guide (2004) Traffic Analysis Toolbox, Volume III: "Guidelines for applying traffic micro-simulation modeling software", Publication FHWA-HRT-04-040. FHWA, U.S. Department of Transportation
18. Transit Capacity and Quality of Service Manual (TCQSM) - 2nd edition, Part 3, Chapter 3, TCRP Report 100, p. 3–29 to 3–34
19. Highway Capacity Manual (2010) Chapter 16, Urban street facilities. p 16–18

Publisher's Note